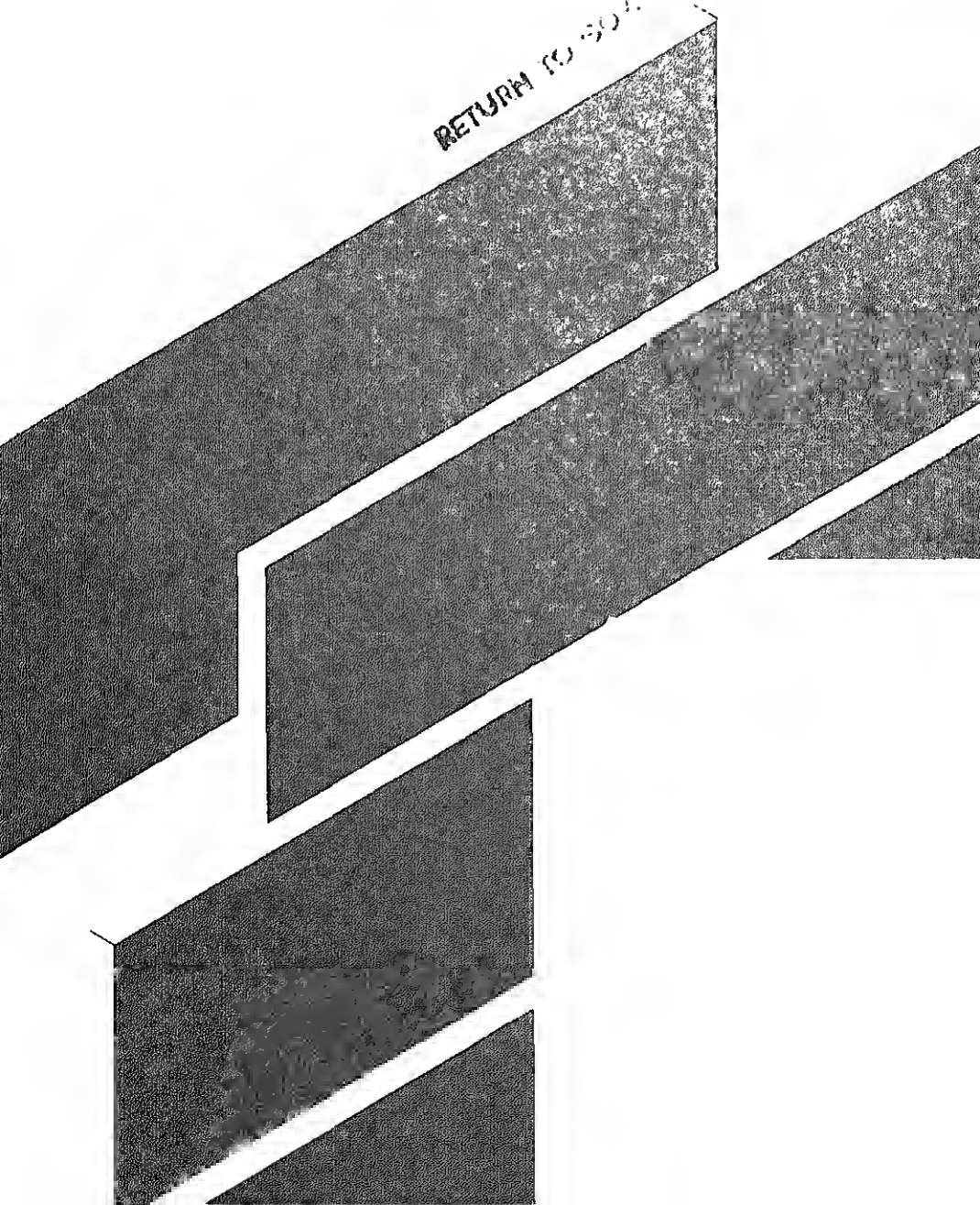


and Construction of Large-Panel Structures

tal Report B "Horizontal Joint Tests"

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DESIGN AND CONSTRUCTION LARGE PANEL CONCRETE STRUCTURES

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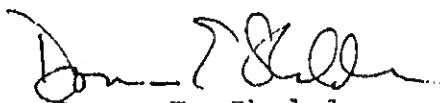
This publication is based on the facts, tests, and authorities stated herein. It is intended for the use of professional personnel competent to evaluate the significance and limitations of the reported findings and who will accept responsibility for the application of the material it contains. Obviously, the Portland Cement Association disclaims any and all responsibility for application of the stated principles or for the accuracy of any of the sources other than work performed or information developed by the Association. The research and studies forming the basis for this report were conducted pursuant to a contract with the Department of Housing and Urban Development (HUD). The statements and conclusions contained herein do not necessarily reflect the views of the U.S. Government in general or HUD in particular. Neither the United States nor HUD makes any warranty, expressed or implied, or assumes responsibility for the accuracy or completeness of the information herein.

FOREWORD

Traditionally, multi-story buildings are so constructed that if a load-carrying member collapses, the entire structure does not: it has an inherent structural integrity. But construction using large-panel concrete members is not traditional. Builders cannot necessarily depend on the new structure's inherent integrity.

To avoid potential problems, the Office of Policy Development and Research has undertaken an extensive research program on large-panel concrete structures. This report, the sixth of nine, deals with horizontal joint tests, and most importantly with the connection of walls to floors.

The research program was supervised for HUD by the late William J. Werner and continued by Ronald J. Moore. Designers, manufacturers, and builders have reason to be grateful to them.



Donna E. Shalala

Assistant Secretary for Policy
Development and Research

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ABSTRACT

This report describes full-scale tests conducted on horizontal to investigate the behavior of wall-to-floor connections in lateral structures. Splitting tests were also made to determine the optimum of reinforcement in the ends of the walls to limit splitting. Test variables included in the test program were strength of grout in the amount of transverse wall reinforcement, and presence of applied moment and rotation. Effects of test variables on joint strength are discussed and a design procedure is proposed.

experimental report on horizontal joints is part of a series of reports leading to the development of a "Methodology for the Design and Construction of Large Panel (LP) Structures." The objective of the tests described in this report was to investigate the behavior of interior and exterior wall-to-floor connections in LP structures.

For the full-scale joint tests and seven splitting tests were made. The specimens consisted of an assembly of precast hollow-core floor slabs and concrete wall elements forming a wall-to-floor connection. The specimens represented a short length of wall from a large panel building. Grout was used to fill the joint between the ends of the floor slabs. The transmission of vertical load through the joint was investigated by applying a vertical compressive force in increments.

In addition, simplified splitting tests were made on specimens consisting of a wall element loaded to represent partial surface loading from a floor slab joint. The objective was to determine the optimum amount of transverse reinforcement in the ends of the wall panels to limit splitting.

The experimental program included the following controlled test variables:

- strength of grout in the joint,
- amount of transverse wall reinforcement,
- filled or unfilled slab cores, and
- applied floor moment and rotation.

The compressive strength of concrete used in the wall panels and the hollow-core slab elements was held constant.

Depending upon the provided combination of test variables mentioned above, the following damage patterns were observed at ultimate load:

- grout crushing,
- wall splitting, and
- slab crushing.

the presence of transverse wall reinforcement increased overall strength of the connection. The optimum amount of wall reinforcement depends on the strength of grout in the joint. With low-strength grouts, the joint strength was increased substantially by filling the slab cores with grout in the connection region. However, in the case of high-strength grouts, filling the slab cores was only effective if the wall panels were adequately reinforced against splitting.

The following conclusions are based on results of the experimental program:

1. Joint capacity increases with grout compressive strength. For high-strength grouts, joint strength is controlled by grout crushing.
2. Wall splitting does not occur when low-strength grout is used.
3. For unreinforced walls, as the grout strength approaches grout compressive strength, the mode of joint behavior changes from grout crushing to wall splitting. Therefore, grout strengths higher than grout compressive strength do not increase joint capacity unless the walls are adequately reinforced. The amount of wall reinforcement required to prevent splitting increases with grout strength.
4. Filling slab cores with grout directly affects joint strength. For low strength grouts are used. However, when medium or high strength grouts are used, filled cores are effective only if the walls are reinforced.
5. Inadequate dry packing below the upper wall panel leads to substantial loss of joint strength.
6. Floor moment and rotation do not have a significant effect on joint capacity.

Various design methods to determine the load capacity of horizontal joints are discussed. A new design procedure is proposed. Comparisons of experimental and calculated strengths for various joint specimens are made.

In addition, details of the experimental program and properties of materials used in the joints, are included as appendices to the report.

Detailed recommendations for specific analysis and design of connections are presented in Report 5.

form "large panel" (LP) concrete structure is used to describe a system composed of precast vertical wall panels with precast floor of panels or planks assembled as shown in Fig. 1. These prefabricated buildings can be considered to be the industrialized form of traditional cast-in-place structural wall (egg crate) construction. Buildings are differentiated by the general arrangement of load-bearing walls as shown in Fig. 2:

-) Cross wall system: in this most prevalent form, load-bearing walls are perpendicular to the longitudinal axis of the building.
-) Spine wall system: for this form load-bearing walls are parallel to the longitudinal axis of the structure.
-) Mixed systems: a combination of cross wall and spine wall system is used.

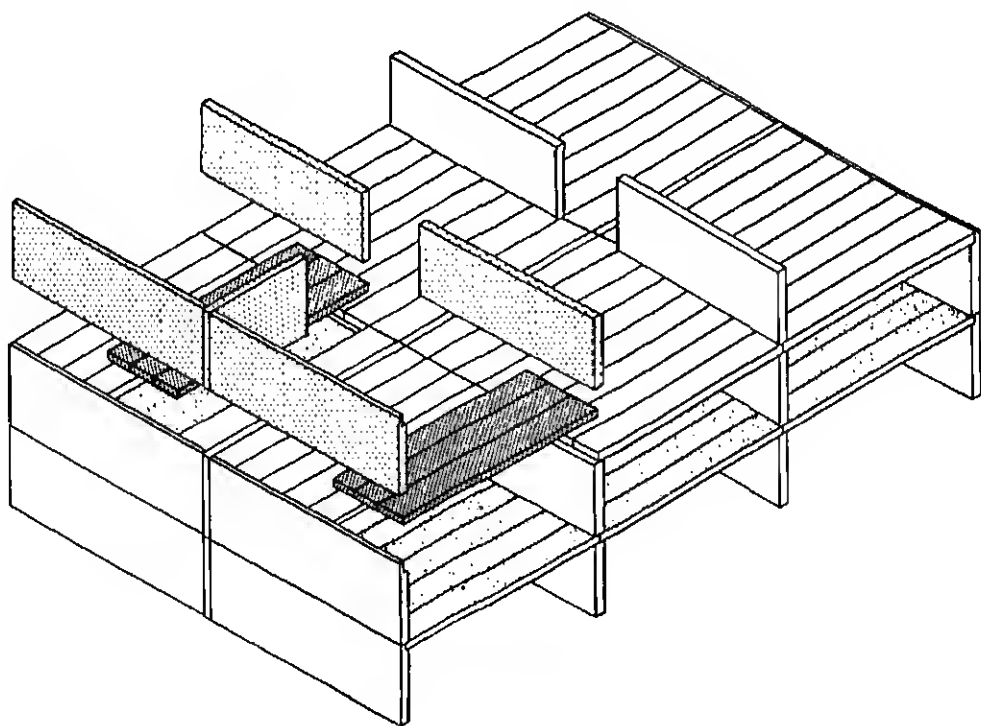
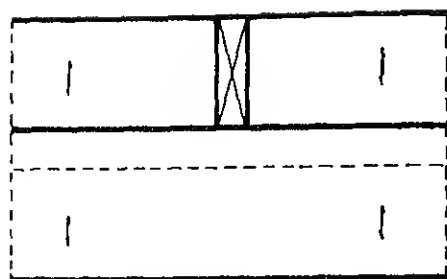
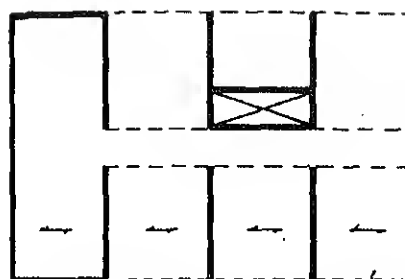


Fig. 1 Isometric View of Idealized Large Panel Structure



(a) Cross Wall System



(b) Spine Wall System

Fig. 2 Idealized Plan Arrangement of Structural Wall Panels in Panel Structures

In most LP systems, the walls transfer their loads directly to the substructure without an intermediate frame. This form of construction restricts plans at any level. Thus it is most typically suited for multistory housing where walls have to be provided between apartments to resist fire and sound transmission. Construction types considered under this investigative program include solid, sandwich, ribbed, hollow core or composite wall panels. Solid, hollow core, or ribbed floor units with or without cast-in-place concrete topping are also included. All elements can be either prestressed or conventionally reinforced.

The overall program objective is to develop minimum criteria for the design and construction of large panel structures. These criteria are being developed to ensure structural safety and serviceability of LP residential buildings, while also providing minimum performance requirements to be used by designers and developers of innovative systems. Development of the criteria will also expand the knowledge of design and construction of large panel structures to a level comparable with that existing for conventional cast-in-place concrete or steel structural systems.

From a structural viewpoint, the essential difference between a cast-in-place concrete structure and a precast large panel structure is the nature of the connections between elements. The function of connections is to transfer loads from one element to another. Ability of large panel structures to perform satisfactorily under all conditions of loading depends upon the integrity of the connections. Connections must transmit gravity loads from floor to floor, from wall to wall, and from wall elements to the foundation. They must also provide for interaction between the various elements and furnish sufficient ductility in resisting lateral loads. If the connections are deficient, strength of the adjoining elements may not be fully utilized.

Connections may be classified (1) as interior horizontal wall-to-wall, interior horizontal wall-to-floor, horizontal floor-to-floor, and vertical wall-to-wall. The main objective of the tests described in this report was to investigate behavior of wall-to-floor connections commonly used in the United States. The report covers tests of both interior and exterior wall-to-floor joints. A single configuration of "Platform Joints" was tested. The compressive strength of concrete in wall panels and hollow-core slab panels and the strength of dry-packed mortar below the upper wall panel were held constant throughout the test series.

Specific analysis and design techniques for types of connections commonly used in LP structures, are presented in Report 5⁽²⁾.

Details of the test setup are shown in Figs. 3 and 4, respectively. Controlled variables included in the test program were:

- (a) strength of grout in the joint,
- (b) amount of transverse reinforcement at the top and bottom panels,
- (c) filled or unfilled slab cores, and
- (d) applied floor moment and rotation.

Design compressive strength of concrete used in the wall and precast floor slab elements was about 5000 psi (34.5 MPa).

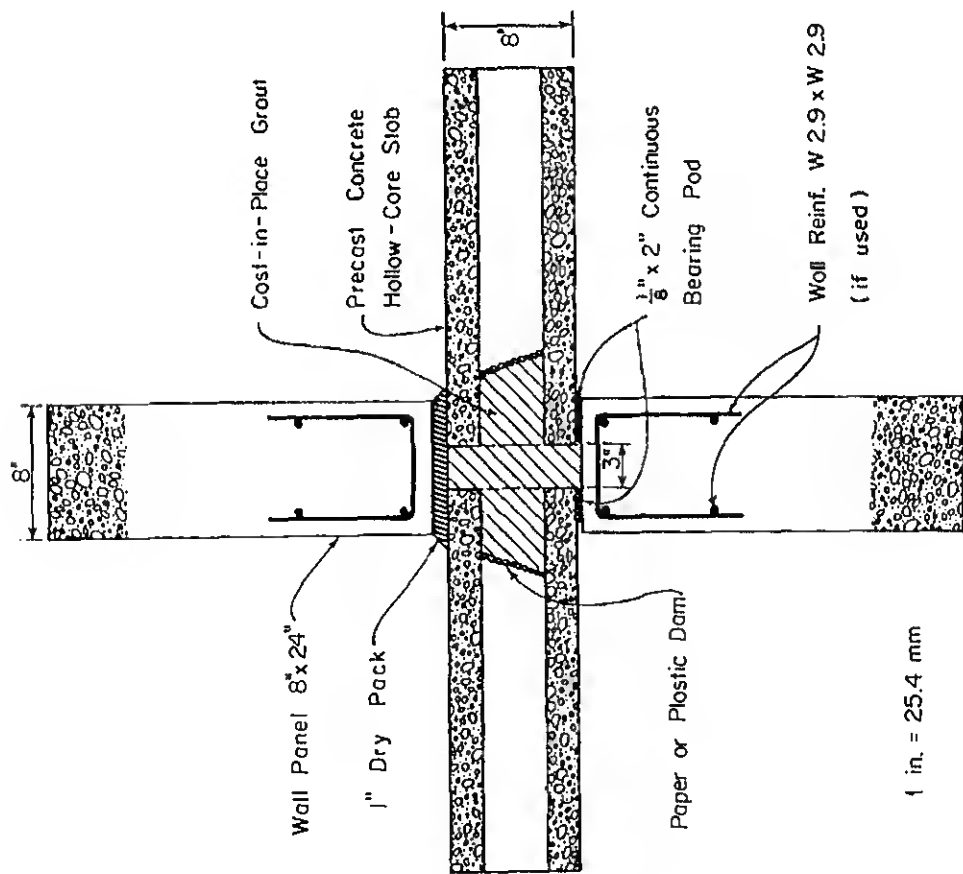
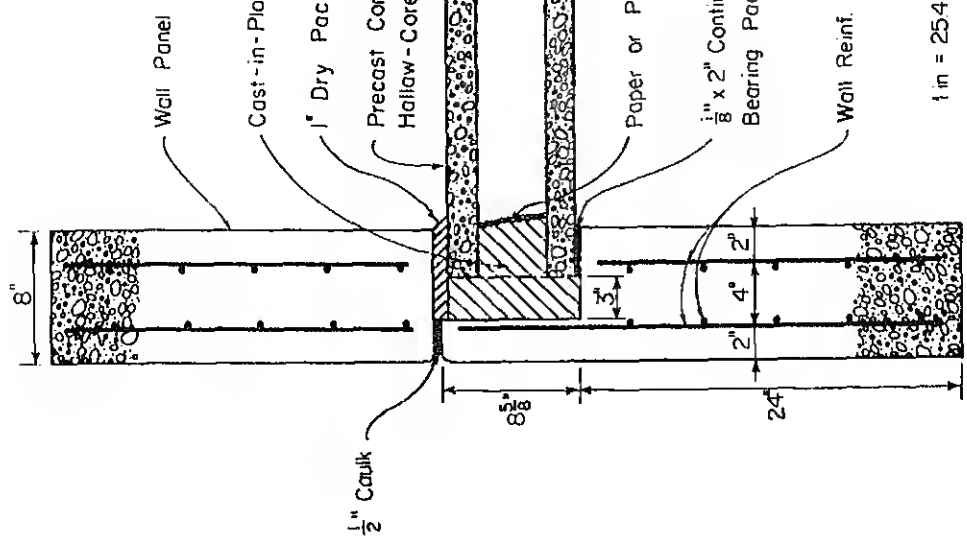
2.1 Test Specimens

Sixteen full-scale wall-to-floor connections and seven splitting specimens were tested. In the connection test, the wall and floor elements consisted of precast concrete hollow-core elements and floor slabs were blocks of precast concrete. Nominal thickness of floor planks were 8 in. (203 mm) and 24 in. (610 mm), respectively.

Detailed descriptions of materials, specimen fabrication, and test procedures are given in Appendix C.

2.1.1 Specimen JM-1

Before beginning the main test program, Specimen JM-1 was tested to determine the influence of applied floor moment and rotation on joint strength. The test was performed using two long slabs on each side of the connection. Test setup and loading arrangement are shown in Fig. 5. Vertical load was applied to the wall in increments by a hydraulic testing machine. Three rams⁽³⁾ were used to apply floor moment by applying



1 in. = 25.4 mm

$$t_{in} = 25.4$$

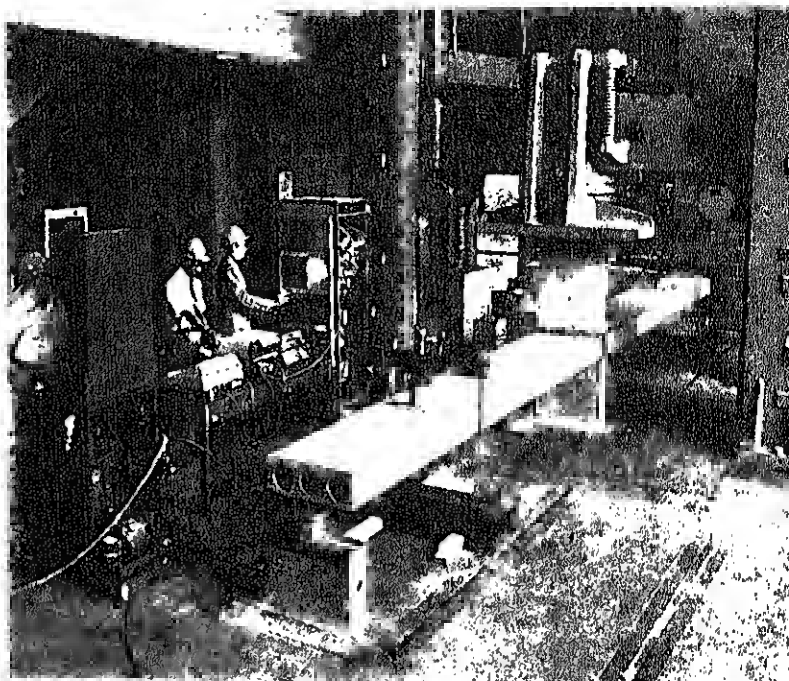


Fig. 5 Test Setup for Specimen JM-1

increased. The load on the slabs was measured by a pair of load cells⁽⁴⁾.

Negative moment introduced at the joint was slightly less than the calculated cracking moment for a 24-in. (0.61 m) wide unit slab. Each floor load was positioned at about the third point from the simply supported end of the slab. This provided a shear ratio of about 5 at the joint. The figure was based on calculations for a 30-ft. (9.14 m) long slab, assumed fixed at both ends.

For Specimen JM-1, grout strength was 3000 psi (20.7 MPa). The top and bottom walls were unreinforced.

2.1.2 Series A - Splitting Tests

Splitting tests were performed to determine the optimum transverse reinforcement needed in the ends of the walls for splitting. Wall blocks were plastered to the base of the testing machine. Vertical load was applied on top through a 3-in. wide by 24-in. (610 mm) long steel plate. This loading responded to the area loaded by the grout column in the joint. Figure 6 shows the test setup for this series. The compressive strength and amount of reinforcement provided for each specimen in this series are shown in Table 1.

2.1.3 Series J and B - Interior Joint Tests

Ten tests were conducted in Series J and B. Figure 7 shows the test setup. A comparison of test results from trial Specimen J-1 indicated that applied floor moment and rotation did not affect joint strength. Consequently, short slabs, without applied floor moment, were used for the remaining tests. However, the blocks were supported at the free ends to prevent rotation.

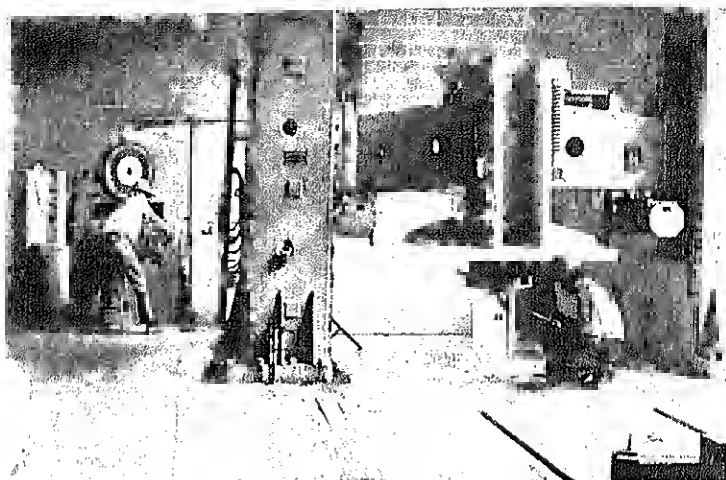


Fig. 6 Splitting Wall Test Setup

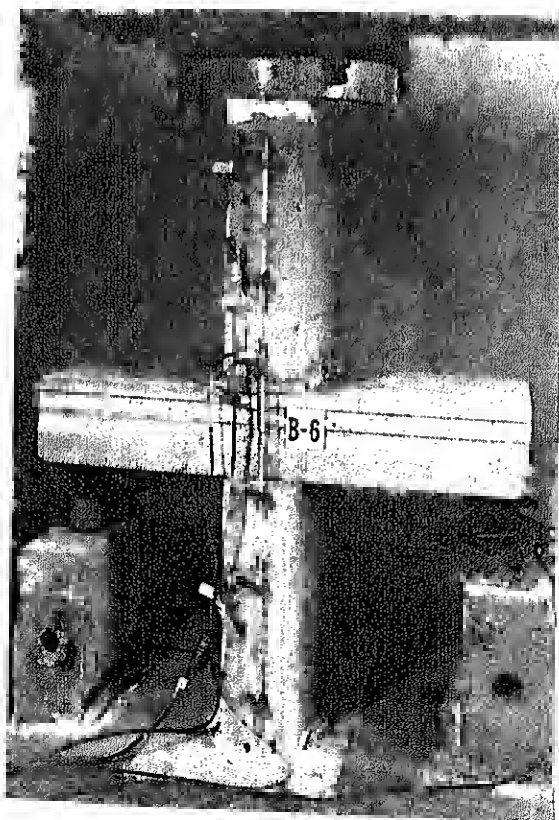


Fig. 7 Interior Joint Test Setup

Specimen Number	Concrete Strength* (psi)	Amount of Wall Reinforcement (in. ²)	Size of Welded Wire Fabric**	Number of Wire
A-1	5040	0	0	0
A-2	4910	0.041	6x6 - W2.1xW2.1	2
A-7	5040	0.082	6x6 - W2.1xW2.1	4
A-3	5040	0.116	6x6 - W2.9xW2.9	4
A-4	4910	0.144	6x6 - W2.1xW2.1	7
A-5	4910	0.227	6x6 - W2.1xW2.1	11
A-6	4910	0.309	6x6 - W2.1xW2.1	15

*Average compressive strength measured on six 6x12-in. cylinders.

**6x6-in. mesh with W2.1 and W2.9 wires corresponds to diameters of 0.162 and 0.192 in., respectively.

Metric equivalents: 1 psi = 6.89 kPa
 1 in. = 25.4 mm

Controlled test variables were:

- (a) strength of grout in the joint,
- (b) amount of transverse wall reinforcement, and
- (c) filled or unfilled slab cores.

Grout strength, amount of wall reinforcement and other details for different interior joint tests are given in Table 2.

2.1.4 Series E - Exterior Joint Tests

Details of exterior joint test specimens are shown in Fig. 4. full-scale tests were conducted. Controlled variables included in the test program were similar to those for interior joints. The test setup is illustrated in Fig. 8. The layout of instrumentation was similar to the interior joints.

Grout strength, amount of wall reinforcement and other details for exterior joints are given in Table 3.

Specimen Number	Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** (in. ²)	Slab Cores Filled or Unfilled	
JM-1***	4860	3000	0	Filled	Pos Dr
J-1	4860	3000	0	Filled	
B-6	5380	2730	0	Unfilled	
B-7	5380	3240	0.116	Unfilled	
B-5	5420	2980	0	Filled	
B-2	5310	3260	0.116	Filled	
B-3A	4810	4510	0.116	Unfilled	
J-2	4820	5000	0	Filled	
J-3	4820	5000	0.116	Filled	
B-4	5310	6800	0.116	Filled	
B-1	4810	4510	0.116	Filled	

*Average compressive strength measured on nine 6x12-in. cylinders.

*6x6-W2.9xW2.9, four cross wires per wall, $A_s = 4 \times 0.029 = 0.116$ in.

*Specimen with long slabs and applied floor moment.

Metric Equivalents: 1 psi = 6.89 kPa.
1 in = 25.4 mm

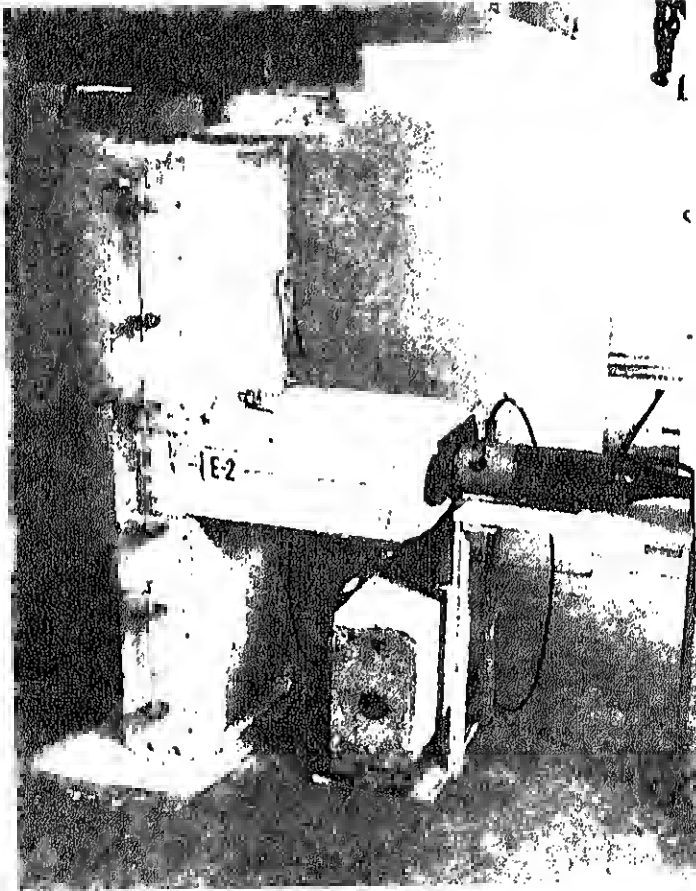


Fig. 8 Exterior Joint Test Setup

Specimen Number	Concrete Strength* (psi)	Grout Strength* (psi)	Amount of Wall Reinf.** (in. ²)
E-1	5420	2980	0
E-2	5180	2840	0
E-3	5180	4770	0
E-4	4900	4630	0
E-5	4900	4510	0.116

*Average compressive strength measured on six 6x12-in. cyl

**6x6-W2.9xW2.9, four cross wires per wall panel, $A_s = 4 \times 0$.

Metric Equivalents: 1 psi = 6.89 kPa
1 in. = 25.4 mm

1.1 Specimen Strength

Measured ultimate loads and relevant data are listed in Table 4. For convenience, these results are expressed both as ultimate load, and as average wall stress. The latter was obtained by dividing ultimate load by the bearing area of the wall panel. Also given in Table 4 are the behavior observations at ultimate load. These are discussed further in Section 3.3.

Measured values of the ultimate load versus wall reinforcement for splitting test series are shown in Fig. 9. The minimum amount of reinforcement to give slightly higher ultimate load in splitting tests was determined as 0.116 in.^2 (75 mm^2). This reinforcement was sufficient to limit wall splitting in the subsequent joint tests. Low to medium strength grouts were used.

1.2 Joint Shortening

Variation of vertical shortening, top wall horizontal strain, and horizontal crack widths with applied loads for Specimen J-2 are shown in Figs. 10, 11, and 12, respectively. Average vertical strain for joint and wall panels was calculated by dividing the total shortening, measured using LVDT's⁽³⁾ by the 10 in. (254 mm) gage length. Plots from other tests showed similar trends.

Joint shortening is due to compression of the grout column and the joint end of each of the floor slabs. Grout strength had a major influence on the amount of shortening. Overall shortening was greater for low-strength grouts. For similar conditions of grout strength and reinforcement, joint shortening in specimens with unfilled slab was at least 33% higher than those with cores filled. Transverse reinforcement reduced measured wall shortening. This was probably due to decreased splitting in reinforced wall panels.

TABLE 4 - TEST RESULTS - INTERIOR JOINTS

Specimen Number	Ultimate Load P_u (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
JM-1	350	1820	4860	3000	Filled	Wall Splitting ⁺	Poor Dry Packing (inadequately packed)
J-1	300	1560	4860	3000	Filled	Wall Splitting ⁺	
B-6	343	1790	5380	2730	Unfilled	Grout Crushing	--
B-7*	360	1870	5380	3240	Unfilled	Grout Crushing	--
B-5	440	2290	5420	2980	Filled	Grout Crushing & Wall Splitting	Both Upper & Lower Walls Split
B-2*	450	2400	5310	3260	Filled	Grout Crushing	--
B-3A*	440	2290	4810	4510	Unfilled	Grout Crushing	--
J-2	465	2420	4820	5000	Filled	Wall Splitting ⁺	--
J-3*	520	2710	4820	5000	Filled	Grout Crushing	--
B-4*	525	2730	5310	6800	Filled	Lower Wall Splitting	Upper Wall & Grout Uncracked
B-1*	266	1380	4810	4510	Filled	Slab Crushing	No Grout Column, Slab Cores Filled

*Wall Panel missing

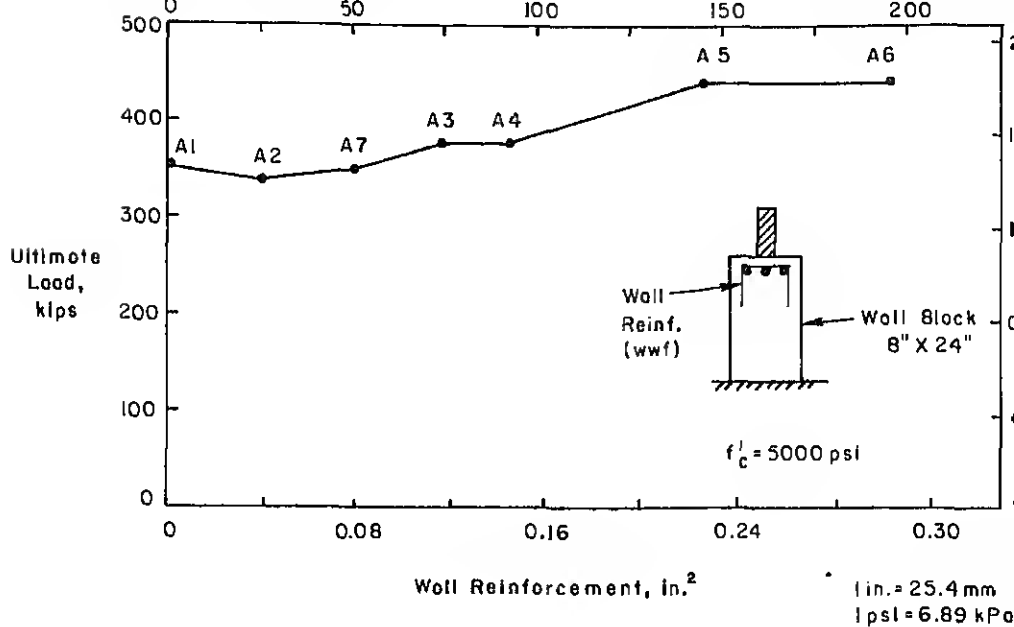


Fig. 9 Splitting Tests - Series A

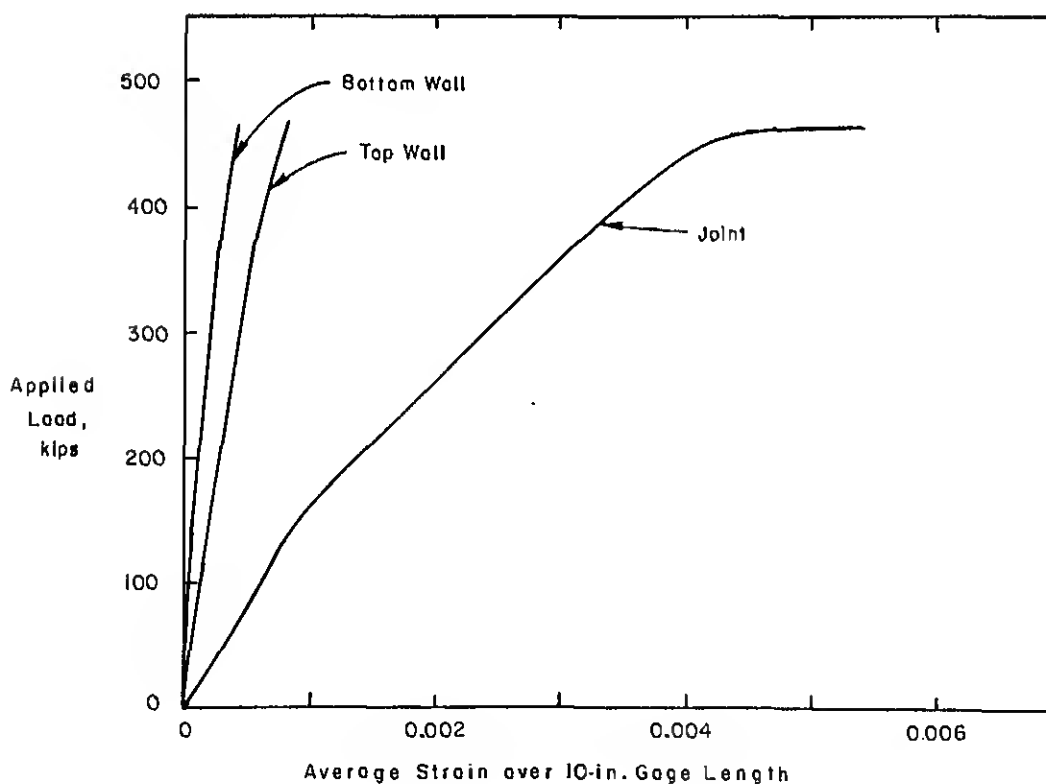


Fig. 10 Load versus Shortening for Specimen J-2

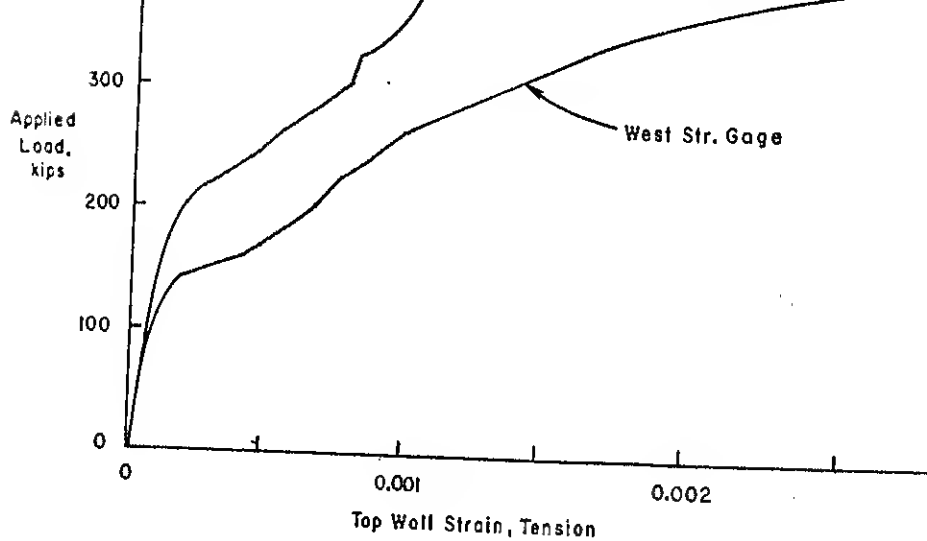


Fig. 11 Load versus Top Wall Strain for Specimen J-2

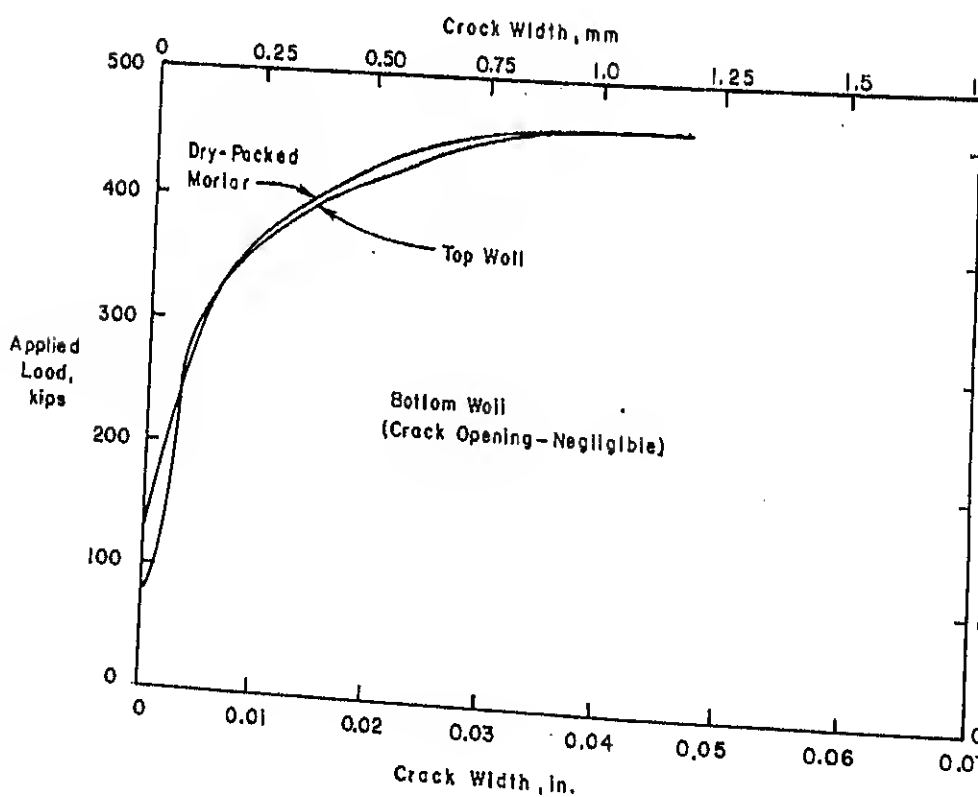


Fig. 12 Load versus Wall Separation for Specimen J-2

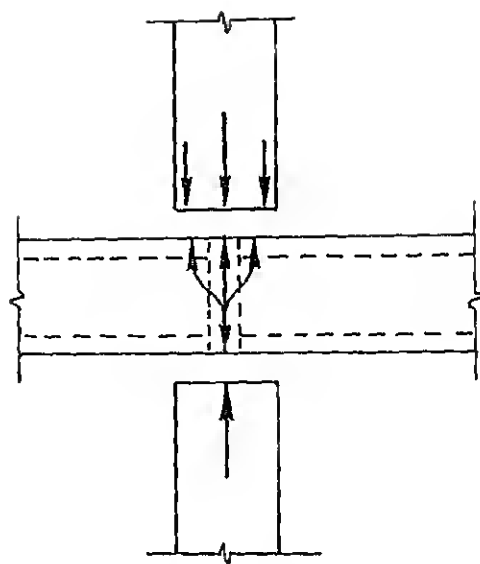
Vertical load can pass through an interior joint from the upper wall to the lower wall in either of two distinct fashions.

In the first case shown schematically in Fig. 13(a), the joint is cast in a monolithic fashion. Stresses across the top of the joint are the most part uniform. However, due to soft bearing pads and grout slabs, the load is funnelled into the bottom of the grout column, creating a stress concentration in the lower portion of the joint as shear stresses are transferred at the slab-grout column interface.

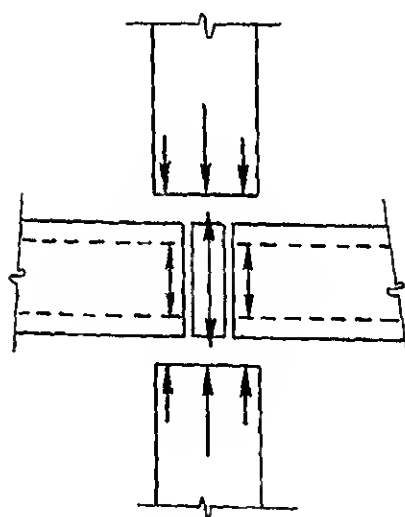
In the second case, shown schematically in Fig. 13(b), the joint consists of three distinct vertical "columns": a grout column in the center and a column on either side. The outer columns consist of the wall slabs and bearing pads. The amount of load that each "column" carries varies with the stiffness of that column in relation to the other two at the joint. Uniform material properties produce generally uniform stress distributions across the joint, while greatly differing properties cause stress concentrations.

For a particular interior joint, load flow patterns and stresses are governed by four variables:

1. Compressive strength of the grout as related to the compressive strength of the wall and slab concrete is one variable. For purposes of discussion, "low", "medium", and "high" strength grouts are defined as having compressive strengths respectively, less than, equal to and greater than the compressive strength of the slab and wall concrete. The slab and wall concrete are assumed to have equal strength.
2. Extension of the grout into the hollow cores of the wall is another variable. Hollow cores are considered filled if the grout extends at least to the plane of the face of the wall.



(a) Before Cracking



(b) After Cracking

Fig. 13 General Behavior - Interior Joints

third variable. The reinforcement consists of nominal vertical and horizontal bars welded to the reverse welded wire fabric as shown in Fig. 3.

4. Stress level in the joint is a fourth variable.

The effects of these variables are discussed in the following :

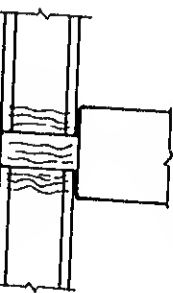
3.3.1 Case 1: Low Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

For Case 1 shown in Fig. 14(a) load flow is through diagonal columns. Since the slab cores are unfilled and the walls themselves are supported on soft bearing pads, the grout column is independent of the slab and carries most of the load. Since the grout strength is less than the wall strength, increasing load results in grout column crushing, identified as Stage 1. With the failure of the grout column, load is transferred to the two slab end columns. At their lower net area these eventually crush before damage to the wall. This is identified as Stage 2. Since the capacity of the grout column is generally greater than that of the corner columns, maximum capacity is reached at Stage 1.

Stresses in the wall panels never control. Consequently, the behavior and capacity of this joint configuration are not improved by reinforcing. This behavior was observed in Specimen B-7. Specimen B-6 after testing is shown in Fig. 15(a).

3.3.2 Case 2: Low Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

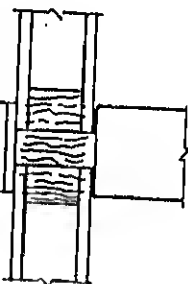
For Case 2 with filled cores as shown in Fig. 14(b), the joint behaves initially as a monolithic element. The funnelling effect is accomplished through shear between the grout column and the grout cores. Vertical stress is initially uniform at the



(a) Low strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

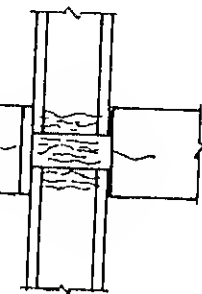
- *1 - Grout Crushes
2 - Slab Ends Crush

Load Stage



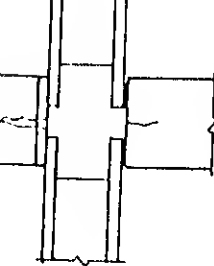
(b) Low Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

- 1 - Grout Cores Shear Off
*2 - Grout Crushes
3 - Slab Ends Crush



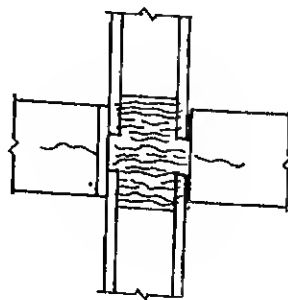
(c) Medium Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

- 1 - Both Walls Crack
*2 - Grout Crushes
3 - Slab Ends Crush



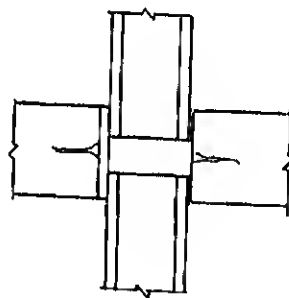
(d) Medium Strength Grout, Cores Unfilled, Walls Unreinforced

- 1 - Grout Cores
2 - Both Walls Crack
*3 - Upper Wall Slab Ends Crush

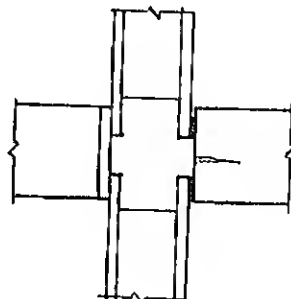


(e) Medium Strength Grout, Cores Filled, Walls Reinforced

- 1 - Grout Cores Shear Off
2 - Both Walls Crack
*3 - Slab Ends Crush

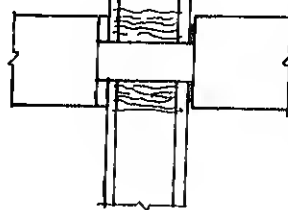


(f) High Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced



(g) High Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

- 1 - Lower Wall Cracks
*2 - Slab Ends Crush

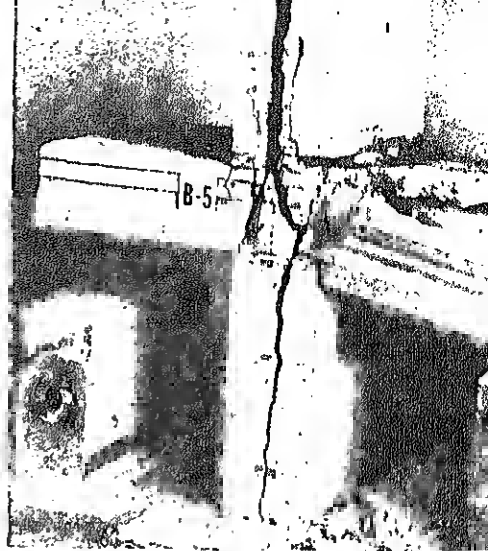


(h) No Grout in Joints, Walls Reinforced or Unreinforced

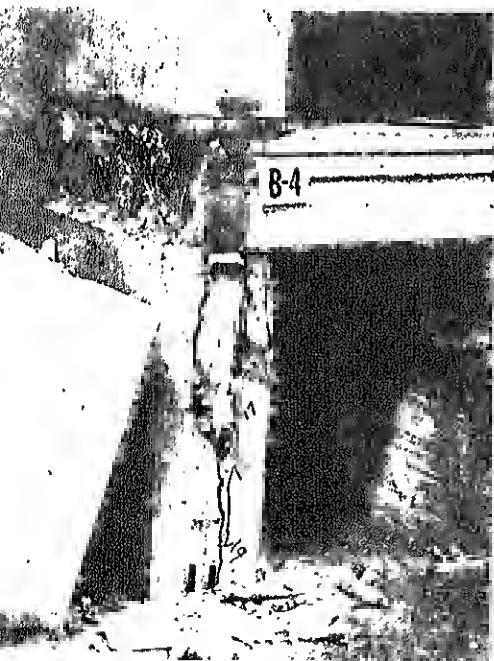
- 1 - Slab Ends Crush



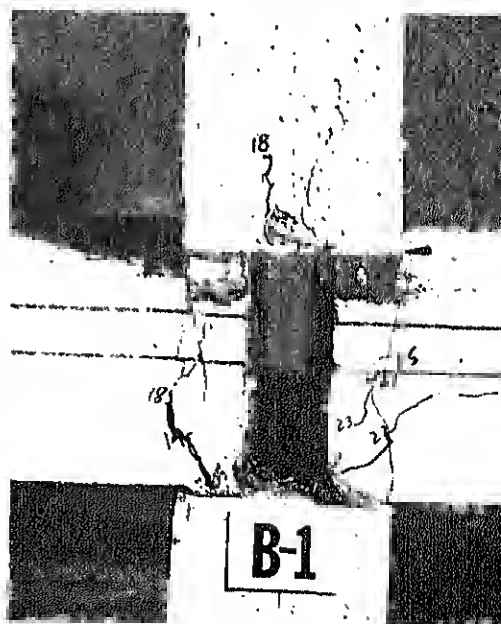
(a) Grout Crushing



(b) Upper Wall Splitting



(c) Lower Wall Splitting



(d) Slab Crushing

Fig. 15 Damage Patterns at Ultimate Load - Interior Jc

grout cores is reached and the grout cores are sheared
grout column. This is identified as Stage 1.

Following Load Stage 1, the load flow is through diaphragm
columns. Due to the soft bearing pads under the diaphragm
grout column carries most of the load. With grout column strength
than wall strength, increased load produces grout column failure
identified as Stage 2, and load is transferred to the wall panels.
Although the slab ends have additional strength due to the grout
cores, they are still weaker than the wall element. The failure of
the slab ends is the final stage. This type of behavior is
evident in Specimens B-2 and B-5. Secondary splitting
also occurred in Specimen B-5, shown in Fig. 15(b). At
the maximum joint capacity is reached when grout column failure
Stage 2. Stresses in the wall panels never become critical,
consequently reinforcing does not affect behavior for this
this joint configuration.

3.3.3 Case 3: Medium Strength Grout, Cores Unfilled Reinforced or Unreinforced

For Case 3 shown in Fig. 14(c), load flow is through diaphragm
tical columns. The soft bearing pads and unfilled grout column
slab ends cause the grout column to support most of the load.
leads to vertical stress concentrations at the wall panels. This
duces horizontal tensile stresses in the walls. As the load
cracks the upper and lower walls, identified as Stage 1. With
increase in load, however, causes grout crushing between the
splits. This is identified as Stage 2. Grout crushing is caused
by load transfer to the slab ends and eventual slab failure
identified as Stage 3. The capacity of the grout column is less
than that of the combined slab ends. As a result, the capacity is
reached at Load Stage 2.

nominal cracks but not high enough to warrant reinforcement. The behavior and capacity of the joint are not expected to be improved by reinforcing. Specimen B-3A containing reinforcement exhibited this behavior.

3.3.4 Case 4: Medium Strength Grout, Cores Filled, Walls Unreinforced

For Case 4 shown in Fig. 14(d), grouted cores cause the walls to respond initially as a monolithic element. Vertical cracks are uniform at the top of the joint and concentrated in the center of the column at the bottom of the joint. As load is increased, the capacity of the medium strength grout cores is reached and the grout cores are sheared off from the grout column. This behavior is identified as Stage 1.

Following Stage 1, load flow is through discrete vertical grout columns. The grout column carries most of the load, but not as much as in Case 3. This is due to the increased stiffness of the grouted end cores versus the ungrouted cores in Case 3. The vertical load concentrations at the wall ends caused by the grout column induce tensile stresses in the walls. Increased load causes cracking in both the upper and lower walls. This is identified as Stage 2.

For the same total vertical wall load, the grout column in Case 4 has slightly lower stress than in Case 3. The difference is due to the need to split the unreinforced walls, identified as Stage 3. This behavior was observed in Specimen J-2, where the upper wall failed first.

3.3.5 Case 5: Medium Strength Grout, Cores Filled, Walls Reinforced

This joint configuration, shown in Fig. 14(e), is identical to Case 4 with the exception of the addition of transverse reinforcement in both upper and lower wall panels. Behavior is identical to that of Case 4 through Load Stage 2. As the load is increased, the capacity of the medium strength grout cores is reached and the grout cores are sheared off from the grout column. This behavior is identified as Stage 1.

grout crushing, identified as Stage 3. Load is then transferred into the slab ends which also eventually crush. This is identified as Stage 4. The capacity of the grout column confined by the slab ends, is generally higher than that of the combined slab ends. Therefore, ultimate capacity is reached when the grout column is crushed at Stage 3. This behavior was observed in Specimen

3.3.6 Case 6: High Strength Grout, Cores Unfilled, Walls Reinforced or Unreinforced

For Case 6 shown in Fig. 14(f), no specimen was tested. Based on observations from the other tests, the behavior is anticipated. Load flow is through discrete vertical columns of soft bearing pads and unfilled cores of the slab ends. The grout column supports most of the load. The grout column has a higher strength than the wall. Consequently, horizontal stresses in the walls, due to the vertical stress concentration, would become critical long before the grout column capacity is reached. Increased load first cracks the upper and lower walls and then splits them. This is identified as Stages 1 and 2 respectively. Splitting will occur whether or not the walls are nominally reinforced.

3.3.7 Case 7: High Strength Grout, Cores Filled, Walls Reinforced or Unreinforced

For Case 7 shown in Fig. 14(g), The grouted cores cause the walls to respond as a monolithic element. Vertical stress is concentrated at the top of the joint and concentrated in the grout column at the bottom of the joint. Under increasing load, the grout column will shear off the grout column because of the increased shear stress of the high strength grout. Instead, the vertical stress concentration at the bottom of the joint causes horizontal tensile stress buildup in the lower wall. These latter stresses become

in load first cracks the lower wall and then splits it. identified as Stages 1 and 2, respectively. Splitting whether or not the walls are nominally reinforced. This was observed in Specimen B-4, shown in Fig. 15(c).

3.3.8 Case 8: No Grout in the Joint, Walls Reinforced or Unreinforced

Case 8, shown in Fig. 14(h), represents an extreme limit. Load flow is solely through the outside slab ends. Capacity joint is reached as the slab ends crush, identified as Stages 1 and 2. Stresses in the wall panel never become critical, consequently behavior and capacity of the joint are not altered by reinforcement. This behavior was observed in Specimen B-1, shown in Fig. 15(a).

3.4 Effect of Variables on Joint Strength

The effects of variables on interior joint strength may be summarized as follows:

1. A change in a variable to cause a more uniform compressive stress across the width of the joint increases the vertical load-bearing capacity of the joint.
2. Under certain circumstances, control of vertical cracks in walls increases the vertical load carrying capacity of the joint.

Based on the variables examined, a list of interior joint configurations is given in Table 5. The purpose of the table is to list the configurations in ascending order of capacity. Behavior of joint configurations that were not tested have been estimated.

TABLE 5 - INTERIOR JOINT CONFIGURATION IN
ASCENDING ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
B-1	JC1	No Grout	No	Either	8	Slab End Crushing
B-6, B-7	JC2	Low	No	Either	1	Grout Crushing
B-2, B-5	JC3	Low	Yes	Either	2	Grout Crushing
B-3a	JC4	Medium	No	Either	3	Grout Crushing
-	JC5*	High	No	No	6	Wall Splitting
J-2	JC6	Medium	Yes	No	4	Wall Splitting
-	JC7*	High	No	Yes	6	Wall Splitting
-	JC8*	High	Yes	No	7	Wall Splitting
J-3	JC9	Medium	Yes	Yes	5	Grout Crushing
B-4	JC10	High	Yes	Yes ^e	7	Wall Splitting

*Rank estimated based on test results for other specimens.

Grout strength ranging from about 2700 psi to 6800 psi (18 46.9 MPa) had a significant effect on joint strength. ultimate loads versus grout strengths for test specimens in Fig. 16. It can be seen that joint strength generally with grout strength, provided the capacity was controlled crushing. However, as indicated in Table 5, for joint c tion JC10, high strength grout alone did not ensure great capacity. As shown in Fig. 16 for Specimen B-4, joint str controlled by wall splitting, and grout strength was never

3.4.2 Transverse Wall Reinforcement

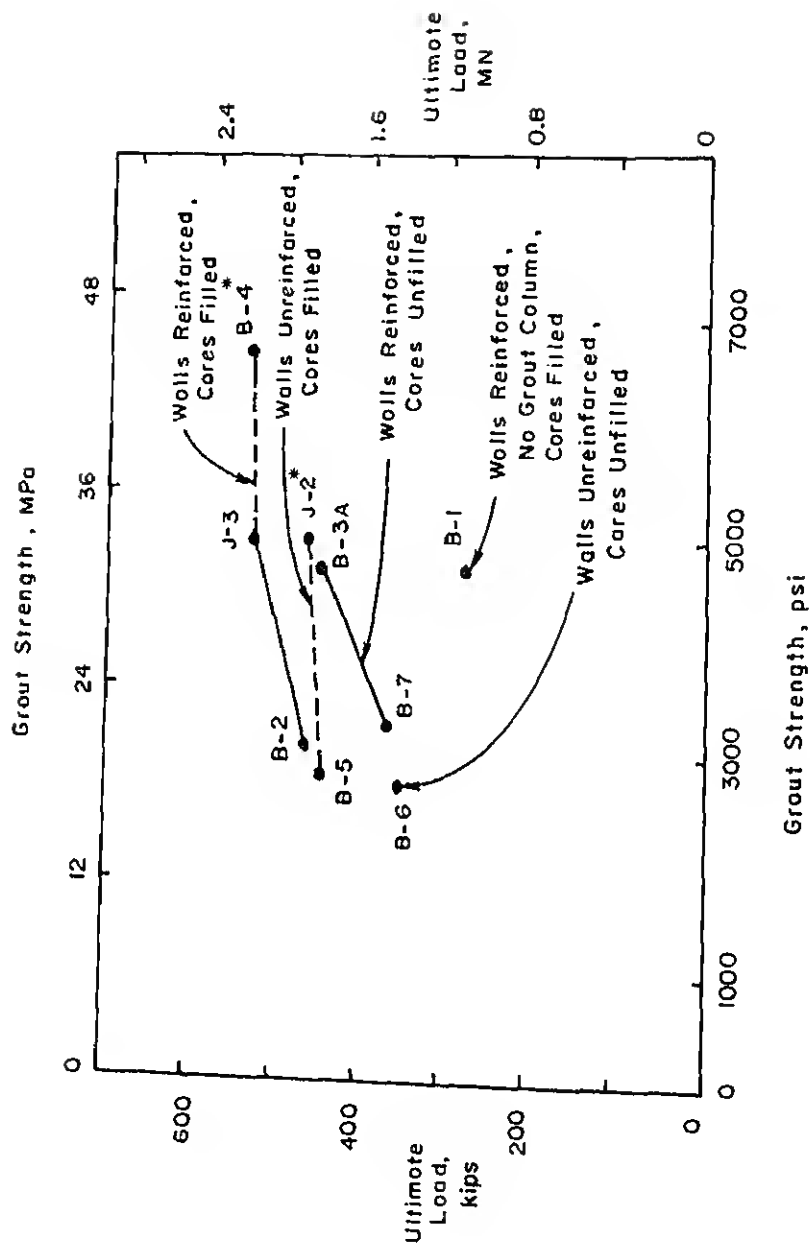
Split resisting reinforcement had no effect on strength configurations JC1 through JC4. In these configuration strengths were controlled by grout crushing. This is shown first four joint configurations of Table 5. Reinforcement the capacity when the strength was controlled by wall spl an unreinforced wall. This corresponds to joint configura and JC9 and was observed in Specimens J-2 and J-3.

3.4.3 Filled Slab Cores

For similar conditions of grout strength and wall reinf the filled cores in the connection region increased joint Filled cores increased the stiffness of the slab ends thereby contributing to a more uniform vertical stress distribution joint. Consequently, crushing of the grout occurred at loads.

3.4.4 Applied Floor Moment and Rotation

Several loading conditions were used to determine the inf moment and rotation on joint strength. The intensity of trated floor load was such that the negative moment intro



* Wall Splitting

Fig. 16. Interior Joint Strength vs. Grout Strength

ratio of about 5 at the joint. The results indicate that moment and rotation do not affect joint strength significantly. Rotation does induce some tensile splitting forces into the wall. However, the effect is minimal and generally neglected.

3.4.5 Dry Packing

In addition to the variables discussed above, joint performance is influenced significantly by the uniformity of dry-pack mortar below the upper wall panel. Well-packed mortar leads to lower stresses below the upper wall. Poor dry packing leads to higher stresses, thereby substantially reducing joint strength and causing premature splitting of the upper wall.

3.5 Experimental Determination of "Stiffness Factor"

Vertical compressive load applied to the upper wall panel is transferred to the lower wall panel through the grout column between the panel and the slabs supported on the bearing pads. A greater part of the load transfer, however, takes place through the grout column. The amount of load transferred through different elements is a function of the relative stiffness of each element in relation to the total stiffness of the connection. Stress flow in the slabs occurs both across the slab depth and in the direction of the load. Therefore, the effective plank stiffness is indeterminate and varies with material properties, load pattern, and geometry of connection. Load transfer is considered based on measurements made on joint and grout column shortening.

3.5.1 Joint Shortening

Joint shortening was measured over a height of about 270 mm. This distance included grout column, dry pack, and 3/4 in. (19 mm) each of top and bottom walls.

different elements as shown in Fig. 17(a). This idealization closely represents conditions in the joint after vertical takes place at the end of each floor element separating column from the grout in the slab cores. Each discrete considered to act independently.

Using the notation given in Fig. 17(a),

$$\sigma = \frac{\delta l_1}{l_1} E_1 = \frac{\delta l_2}{l_2} E_2 = \frac{\delta l_3}{l_3} E_3 = \frac{\delta l_4}{l_4} E_4$$

$$\delta l_3 = \delta l - \delta l_1 - \delta l_2 - \delta l_4$$

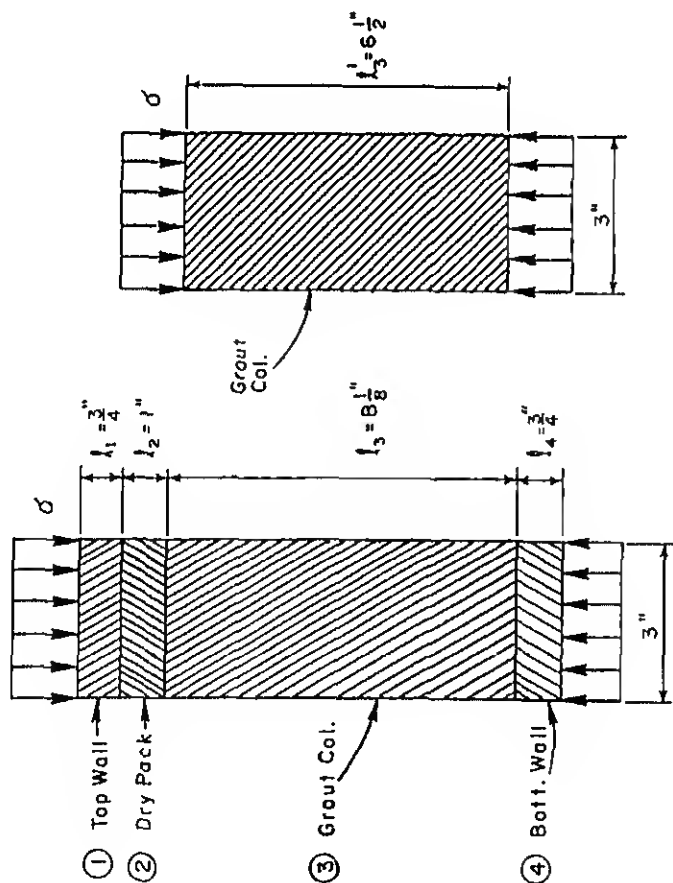
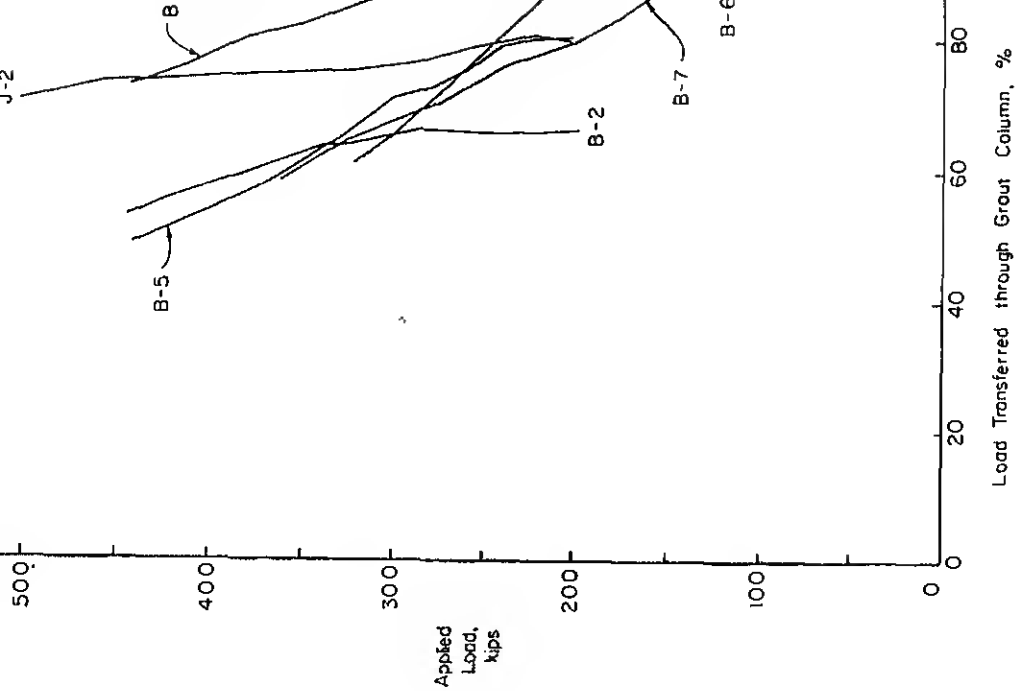
$$= \delta l - \sigma \left(\frac{l_1}{E_1} + \frac{l_2}{E_2} + \frac{l_4}{E_4} \right)$$

where σ = uniform vertical stress in column,
 $\delta l_1, \delta l_2, \delta l_3, \delta l_4$ = shortening over heights $l_1, l_2, l_3,$ and l_4 respectively,
 Elements 1, 2, 3, 4, respectively,
 δl = measured joint shortening = $\delta l_1 + \delta l_2 + \delta l_3 + \delta l_4$, and
 E_1, E_2, E_3, E_4 = modulus of elasticity of Elements 1, 2, 3, and 4, respectively.

The shortening in grout column, δl_3 , was determined from expression by assuming a uniform vertical stress, σ , and corresponding values of E_1, E_2 and E_4 from a stress-strain curves plotted for materials of different strengths. A trial and error method was used to match the vertical stress with the grout column stress corresponding to the calculated grout column shortening δl_3 .

Therefore, the amount of load transferred through the grout column, P_g , is given by:

$$P_g = \frac{\delta l_3}{l_3} (E_3) (A_g)$$



(a) Joint Shortening

(b) Grout Column Shortening

Fig. 17 Idealized Uniform Stress Region

3.5.2 Grout Column Shortening

Stress analysis based on total joint shortening described in Section 3.5.1 was quite complex. It involved materials with different elastic properties. The voids left between different materials as a result of construction procedures and subsequent shrinkage were not considered in the analysis. This resulted in a high calculated percentage of load transferred through the grout column in the initial load stages.

Shortening in the grout column alone was also measured in Specimens B-6 and B-7. Strain measurements were taken over a height of about 6.3 in. (160 mm).

Assuming a uniform stress throughout the length of the grout column as shown in Fig. 17(b), the percentage of applied load transferred through the grout column was calculated.

$$\sigma = \frac{\delta \ell'_3}{\ell'_3} E_3 \quad (\text{Eq. } 3.5.2)$$

where $\delta \ell'_3$ = shortening over height ℓ'_3 of grout column

Therefore, the amount of load transferred through the grout column is given by:

$$P_g = \frac{\delta \ell'_3}{\ell'_3} (E_3) (A_g) \quad (\text{Eq. } 3.5.3)$$

Using the procedure described in Sections 3.5.1 and 3.5.2, the percentage of load transferred through the grout column was calculated.

ized column by cracking at the slab end and grout column face. Results for Specimens J-3 and B-4 are not plotted due to inconsistent data. Figure 18 shows that the percentage of load transferred through the grout column decreased as the load on the slab increased.

4.1 Specimen Strength

Ultimate test loads are given in Table 6. For convenience, these results are expressed both as ultimate load, P_u , and as average wall stress. The latter was obtained by dividing the ultimate load by the bearing area of the wall panel. Also given in Table 6 are the observations at ultimate load indicating that crushing of the grout occurred in all specimens.

4.2 General Behavior

As in interior joints, vertical load can pass through an exterior joint in either of two fashions. In the case shown schematically in Fig. 19(a), the joint functions in a monolithic manner. Load is distributed across the top, nonuniformly due to the built-in eccentricity of the joint. At the bottom of the joint, load is funnelled into the grout column due to the soft bearing pads beneath the ends of the slabs.

In the case shown in Fig. 19(b), the joint consists of two discrete vertical "columns": a grout column in the center and a column on one side consisting of the end of the slab. The load that each "column" supports varies with the total stiffness of that column and the eccentricities present within the exterior joint. As there exists a significant built-in eccentricity because of the discrete slab end on only one side, uniform material properties will not produce uniform stresses across the joint, as in the case of interior joints.

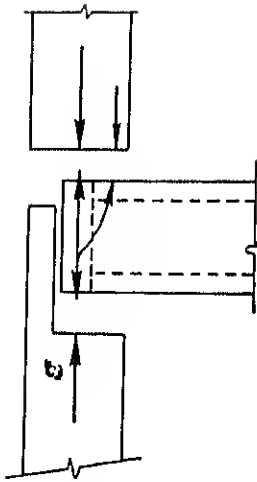
For a particular exterior joint, both load flow patterns and behavior are governed by the same four variables as interior joints described in Section 3.3. However, in exterior joints the effects are much less pronounced. As noted above, the basic configuration of the joint leads to nonuniform stresses no matter what the material properties may be. As shown schematically in Fig. 19(c), the joint initially tends to transfer most of the load to the centrally located grout column. Consequently

TABLE 6 - TEST RESULTS-EXTERIOR JOINTS

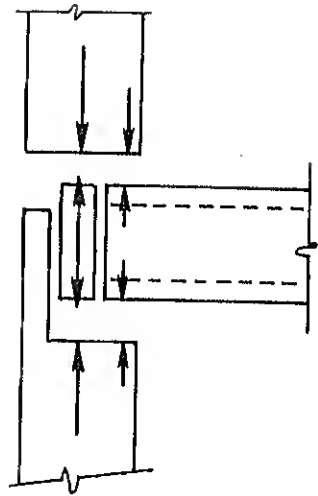
Specimen Number	Ultimate Load P_u (kips)	Average Wall Stress** (psi)	Wall Panel Concrete Strength (psi)	Grout Strength (psi)	Slab Cores Filled or Unfilled	Observations at Ultimate Load	Remarks
E-1	300	1560	5420	2980	Filled	Grout Crushing	--
E-2	290	1510	5180	2840	Unfilled	Grout Crushing	--
E-3	280***	1460	5180	4770	Unfilled	Grout Crushing	Poor Dry Packing (inadequately packed)
E-4	380	1980	4900	4630	Filled	Grout Crushing	--
E-5*	400	2080	4900	4510	Filled	Grout Crushing	--

*Wall Panels reinforced with 6x6 - W 2.9 X W 2.9, $A_s = 0.116 \text{ in.}^2$

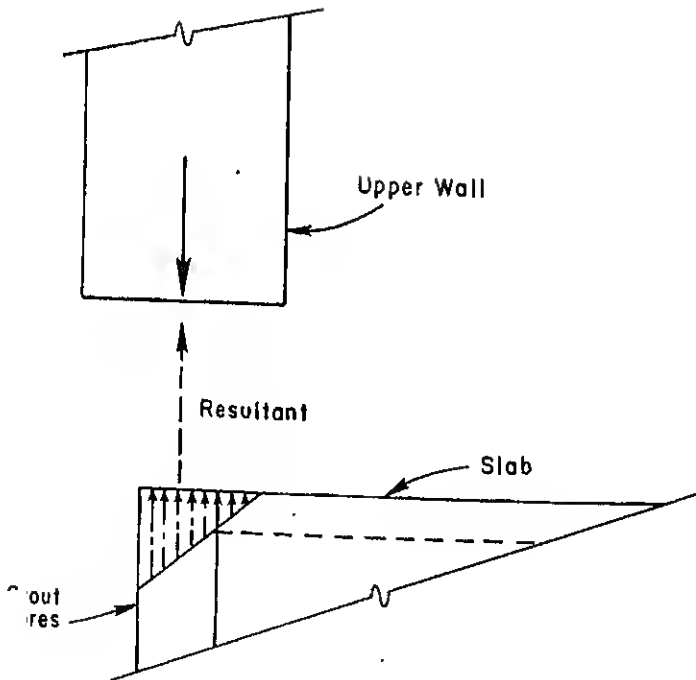
**Average wall stress obtained by dividing the ultimate load by the bearing area of wall panel (bearing area is 24x8 in.)



(a) Before Cracking



(b) After Cracking



) Nonuniform Stresses Prior to Ultimate load

General Behavior - Exterior Joints

grout column to the lower wall is substantially higher than in interior joints when compared to similar interior joints.

4.2.1 Case 1: Low and Medium Strength Grout, Cores Filled or Unfilled, Walls Reinforced or Unreinforced

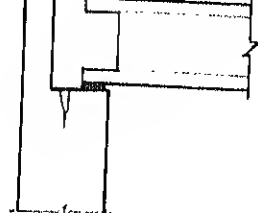
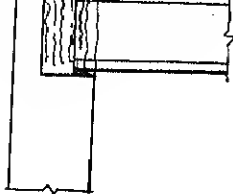
For Case 1, shown in Fig. 20(a), load flow is through diagonal columns when cores are unfilled, and through a central element when cores are filled. In the latter cases, horizontal grout carries most of the load. As load is increased, the grout is crushed before tensile splitting stresses, caused by the stress concentration, become critical in the wall panel. This is identified as Stage 1.

With the loss of the grout column, load is transferred to the slab ends, which also crush, identified as Stage 2. Since the capacity of the grout column is greater than that of the slab ends, the load is reached at Stage 1.

Stresses in the wall panel never become critical. Therefore, the behavior and capacity of this joint configuration are not improved by reinforcing. A specimen exhibiting this behavior is shown in Fig. 21. Similar behavior was observed in all specimens tested to ultimate load.

4.2.2 Case 2: High Strength Grout, Cores Filled or Unfilled, Walls Reinforced or Unreinforced

No specimens representing Case 2, shown in Fig. 20(b), were tested. The load flow is similar to that of Case 1. Due to the soft bearing of the wall and to the soft bearing pads beneath the slab ends, the grout again transfers most of the load. The grout has a higher strength than the wall concrete. Consequently, it is expected that horizontal tensile stresses in the walls, caused by vertical stress concentration, would become critical before the grout column capacity is reached.



(a) Low & Medium Strength Grout
Cores Filled or Unfilled,
Walls Reinforced or Unrein-
forced

(b) High Strength Grout, C
Filled or Unfilled, Wa
Reinforced or Unreinfor

*1 - Grout Crushes
2 - Slab Ends Crush

1 - Both Walls Crack
*2 - Both Walls Split

*Ultimate Capacity

Fig. 20 Behavior at Successive Load Stages - Exterior Joints



Fig. 21 Damage Pattern at Ultimate Load - Exterior Joints

tively. Splitting would likely occur whether or not the wall was nominally reinforced.

4.3 Effects of Variables on Joint Strength

Grout strength was the only variable in the test program that affected the strength of the joint. This occurred because the basic configuration of the joint caused most of the load to be transferred through the grout column.

Based on the variables examined, a list of exterior joint configurations is given in Table 7. The table lists joint configurations in order of capacity. Behavior of the last two joint configurations, JC13 and JC14, have been estimated.

4.3.1 Strength of Grout

Grout strength ranging from approximately 2800 psi to 33,100 psi (19.3 MPa to 33.1 MPa) had a significant effect on joint strength. Measured ultimate loads versus grout strength are shown in Figure 4.3.1. It can be seen that with the exception of Specimen E-3, which was poorly dry packed, joint strength increased with grout strength.

As suggested in Table 7 for configuration JC13 and JC14, the capacity of joints with high strength grout is expected to be limited by wall splitting.

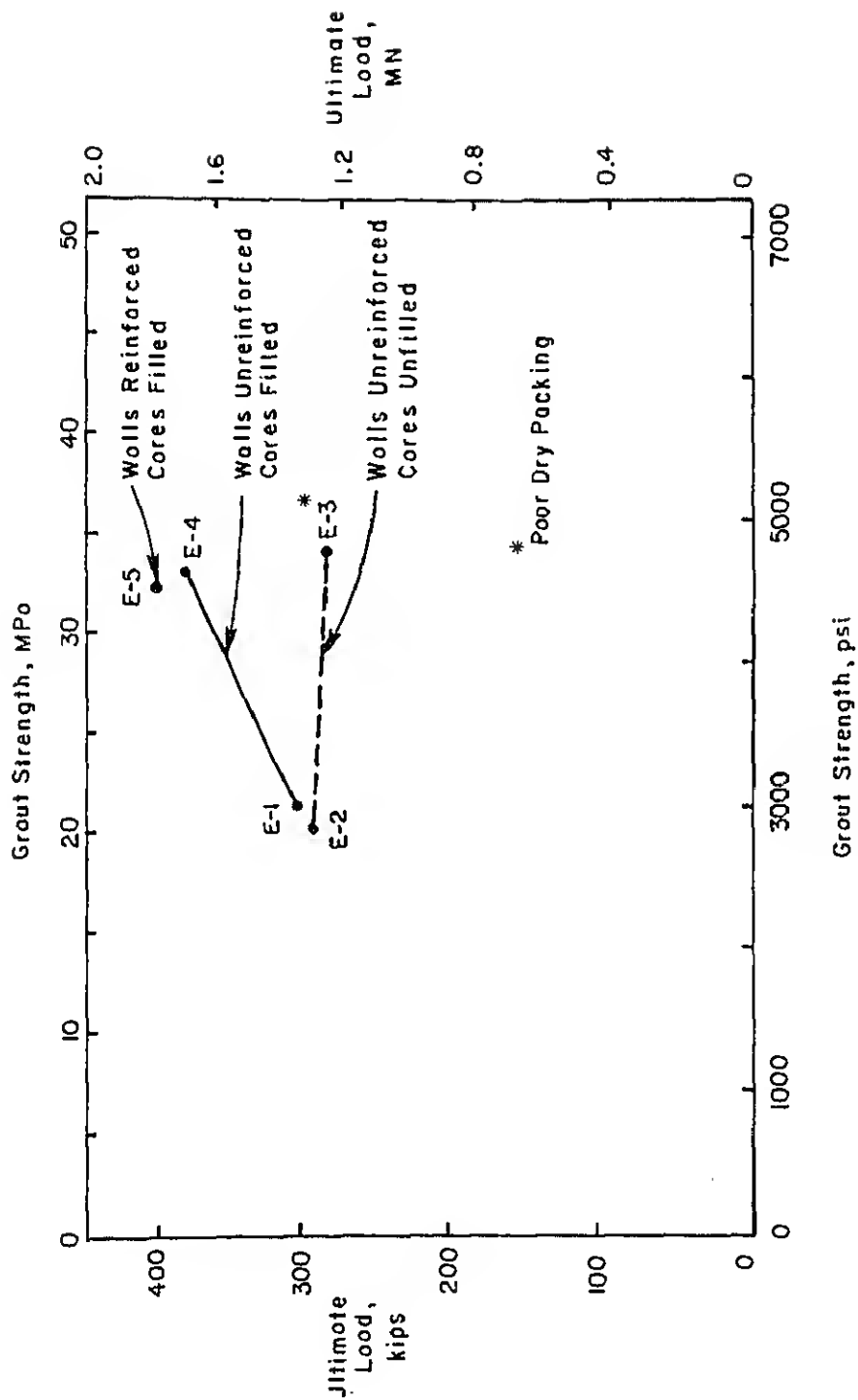
4.3.2 Transverse Wall Reinforcement

Addition of split-resisting reinforcement has no effect on joint strength with low or medium strength grout. Reinforcement will increase joint capacity only when the mode of behavior at ultimate is wall splitting in a non-reinforced wall. Joint configurations JC13 and JC14 would be expected to perform this way.

TABLE 7 - EXTERIOR JOINT CONFIGURATION IN ASCENDING
ORDER OF CAPACITY

Specimen	Joint Configuration	Strength of Grout	Cores Filled	Walls Reinforced	Behavioral Case	Behavior at Ultimate
E-1, E-2	JC11	Low	Either	Either	1	Grout Crushing
E-3, E-4, E-5	JC12	Medium	Either	Either	1	Grout Crushing
--	JC13*	High	Either	No	2	Wall Splitting
--	JC14*	High	Either	Yes	2	Wall Splitting

*Rank estimated based on test results for other specimens.



Filling the cores in the connection region increases the capacity. As the exterior joints have a slab on one side of joint only, lesser load is transferred through the slab compared to the interior joints. Therefore, filling the cores in exterior joints will have somewhat less of an effect.

4.3.4 Dry Packing

Poor dry packing can lead to premature joint failure. Dry packing is more difficult in exterior joints, because mortar has to be packed from one side of the joint only. Consequently, the probability of inadequate packing is higher.

1 Prestressed Concrete Institute Methods

In recent years, several methods to determine the load capacity of horizontal connections in large panel structures have been proposed. This section discusses three design procedures proposed by the Prestressed Concrete Institute (PCI)⁽⁵⁾.

Prestressed Concrete Institute Method 1⁽⁵⁾ is based on strengths of joint components. Applied design load on the joint is distributed to the components of the joint according to the stress-deformation strength characteristics of the components. It also allows a "confined concrete factor" on the cylinder strength of concrete or grout in the joint.

This method is empirical in nature, and is complex to use. There is a lack of experimental data to verify the stress-strain relationships used in the analysis. Elastic properties of the bearing pads used in the experimental tests described in this report differed substantially from values suggested in PCI Method 1.

Prestressed Concrete Institute Method 2⁽⁵⁾ is based on elastic analysis of a joint. With this approach, the joint is divided into a series of discrete vertical "columns." The amount of load that each "column" supports is a function of the stiffness of that particular column. The method permits determination of the stress distribution in the components of the joint under service load conditions. However, Method 2 has the following limitations:

1. It underestimates the effective stiffness of a slab by limiting the width of the "slab column" to the bearing length of the floor slab in calculating areas of discrete vertical "columns." However, analytical investigations⁽²⁾ indicate that additional plank length beyond the edge of a wall participates in transferring vertical load from the upper

2. It does not consider the use of hollow-core slabs and the additional stiffness provided by the grout in the slab cores in the connection region.
3. It permits determination of stresses in the elastic range, not the load capacity of a joint. Also, the method does not consider the effect of wall reinforcement or the possibility of a splitting failure when high strength grout is used.

Prestressed Concrete Institute Method 3⁽⁵⁾, is based mainly on tests conducted by the Danish Structural Research Center. Their empirical expression seems valid, but is applicable only if grout strengths in the joint and the wall concrete strength are similar.

5.2 Proposed Design Procedures

5.2.1 Interior Joints

Vertical compressive load applied to the upper wall is transferred to the lower wall through the grout column and the floor and slabs. A greater part of the load is carried by the grout column and slabs carry the rest. Ultimate load, P_u , can be separated into two parts as follows:

$$P_u = P_g + P_s$$

where

P_u = joint strength

P_g = amount of load transferred through the grout column

P_s = amount of load transferred through the floor slabs

The amount of load transferred through slabs can be increased if the cores are filled. It should be noted, however, that, P_s , does not represent the load capacity of an ungrouted connection.

crushed. Strength of an ungrouted connection will, usually, be much higher than P_s . This strength can be determined directly from the bearing area of slab ends and the compressive strength of floor slab concrete.

The proposed method limits the maximum useable grout strength f_u , and thus, ensures that joint capacity is controlled by grout crushing rather than wall splitting. The maximum useable grout strength, and consequently joint capacity can, however, be increased by selecting proper joint variables, such as grout and wall strengths, wall reinforcement, and by filling the slab cores. Therefore, high strength grout can only be used effectively if walls use high strength concrete, they are reinforced against splitting, and the slab cores are filled with grout.

Based on the maximum useable grout strength, f_u , the following expression for capacity of interior horizontal joints was developed:

$$P_g = K P_u$$

$$P_s = (1 - K)P_u$$

From basic principles,

$$P_g = t L f_u$$

where t = width of the grout column - in this case 3 in (76 mm),
 L = horizontal length of grout column,
 f_u = maximum useable strength of grout defined as follows: compressive strength of grout, or wall concrete, f'_c , whichever is less, not more than 4000 psi (27.6 MPa), unless walls are reinforced against splitting and slab cores are filled with grout,

load transferred through the grout was found to increase linearly from value of 0.65 for a grout strength (17.24 MPa) to a value depending of grout in the joint, f_g .

For simplicity, K can be taken as follows:

$$\begin{aligned} K &= 0.65 + \left[\frac{f_g - 2500}{50,000} \right] \text{ for } f_g \text{ in psi,} \\ &= 0.65 + \left[\frac{f_g/0.0069 - 2500}{50,000} \right] \text{ for } f_g \end{aligned}$$

Therefore, $P_u = P_g/K$

The filled core factor, C, can be used to account for strength due to increased slab stiffness. The filled is inversely proportional to the square root of grout strength, f_g .

Therefore, $P_u = \frac{t L}{K} f_u C$

where C = filled core factor determined as follows

For filled slab cores:

$$\begin{aligned} C &= 1.4 \sqrt{\frac{2500}{f_g}} \text{ for } f_g \text{ in psi, or} \\ &= 1.4 \sqrt{\frac{2500}{f_g/0.0069}} \text{ for } f_g \text{ in MPa,} \end{aligned}$$

but not less than 1.0

For unfilled slabs cores:

$$C = 1.0$$

applicable to other types of joints with different geometric and material properties. However, the configuration used in this investigation is representative of horizontal joints used in large structures.

5.2.2 Exterior Joints

It appears from the tests that for exterior joints, most of the load applied to the upper wall panel is transferred to the lower wall panel through the grout column. Stiffness provided by the slab may, therefore, be ignored.

Therefore, $P_u = P_g$

Based on the experimental study on exterior joints, the following expression is proposed for determining a conservative value for joint strength:

$$P_u = t L f_u C$$

where

P_u = joint strength,

t = width of grout column - in this case 3 in. (76 mm),

L = horizontal length of grout column,

f_u = maximum useable strength of grout determined as follows: compressive strength of grout, f_g , and wall concrete, f'_c , whichever is less, but not more than 4000 psi (27.6 MPa), unless the slab cores are filled with grout,

f_g = compressive strength of grout in the joint,

C = filled core factor determined as follows:

For filled slab cores:

$$C = 1.2 \sqrt{\frac{2500}{f_g}} \quad \text{for } f_g \text{ in psi, or}$$

but not less than 1.0

For unfilled slab cores:

$$C = 1.0$$

It should be noted that the above expression is based on a number of tests applied to one type of joint configuration. It may not be applicable to other types of joints with different geometrical or material properties. However, the configuration used in this investigation is representative of horizontal joints commonly used in large panel structures.

5.3 Comparison of Measured and Calculated Strengths

Strengths for the interior joint specimens were calculated from three PCI Methods and from the proposed design expression. These were compared with the measured strengths. The values are listed in Table 5.1.

Prestressed Concrete Institute Method 1 is based on stress-deformation characteristics of the joint components. An increase in grout strength is allowed due to its confined nature in the joint. However, the method does not distinguish between slab cores filled and unfilled. The maximum value of confinement factor is arbitrarily fixed at 2.0. In calculating the load capacities using this method, confinement factors of 2.0 and 1.0 were assumed for slab cores filled and unfilled, respectively. Furthermore, there is no provision for additional joint strength due to reinforcement in wall panels, or loss of strength due to wall splitting or to grout crushing in unreinforced wall panels. Consequently, the calculated strengths of Specimens J-2, J-3 and B-4 were substantially different from measured strengths.

Prestressed Concrete Institute Method 2 gives stress distribution under service load conditions only. In calculating the load capacity of joint specimens, the maximum stress in the grout was assumed to be the

Specimen Number*	Calculated Load Capacity (kips)				Measured Strength (kips)
	PCI Methods			Proposed Method	
	1	2	3		
B-6	211	286	252	300	343
B-7	249	332	299	351	360
B-5	460	309	275	417	440
B-2	502	334	301	433	460
B-3A	344	445	417	417	440
J-2	761	488	462	411	465
J-3	761	488	462	496	520
B-4	1028	642	628	519	525

Specimens JM-1 and J-1 have been omitted because their failure was due to poor dry packing. Specimen B-1 has been excluded because there was no grout column provided.

See Table 2 for strength of grout, concrete and other variables.

Conversion equivalent: 1 kip = 4.448 kN

From this method, the stress or load distribution at ultimate was assumed to be the same as at service load. Also, since this method does not take into account the effect of splitting in the walls, calculated strengths of Specimens J-2 and B-4 are overestimated. These specimens contained high strength grout. Wall splitting occurred before the grout crushed. There is no provision for added joint strength due to filled grout cores. Therefore, calculated strengths of Specimens B-2 and B-5 are underestimated.

Prestressed Concrete Institute Method 3 is applicable only when concrete and wall strengths are approximately equal. For the present tests,

However, strength of Specimen J-3 with reinforced wall panels, was underestimated. Values for grouts with lower and higher strengths are also given in Table 8 for comparison. In these specimens, agreement between calculated and measured strengths is poor.

Out of all the methods proposed prior to the present research, Method 2, based on elastic analysis of a joint provided the most reasonable approach for designing interior wall-to-floor connections. However, as described earlier in this section, this method gives stress distribution in the elastic range only, and it does not consider the cases where joint capacity is limited by wall splitting. Consequently, the use of this method for predicting joint strength is very limited.

The proposed design method described in Section 5.2 is based on the present experimental investigation. It predicts the joint capacity taking into account all modes of joint behavior both under service and inelastic loading conditions. As shown in Table 8, the load capacity calculated by the proposed method agrees very favorably with the measured joint strengths.

Capacities for exterior joint specimens were also calculated from the proposed design expression. A comparison with measured values is given in Table 9.

Specimen Number*	Joint Strength** (kips)	
	Calculated by Proposed Method	Measured
E-1	236	300
E-2	204	290
E-3	288	280*
E-4	333	380
E-5	325	400

*Specimen E-3 has reduced joint capacity due to poor dry packing.

**See Table 3 for strength of grout, concrete and other variables.

Metric equivalent: 1 kip = 4.448 kN

6.1 Interior Joints

1. Joint capacity increases with grout compressive strength. Joint strength is controlled by grout crushing. This occurs when the grout strength is less than about 80% of concrete compressive strength.
2. Wall Splitting is not a problem when low-strength grout is used. However, for unreinforced walls, when the grout compressive strength exceeds about 80% of wall concrete compressive strength, wall splitting occurs prior to grout crushing. When the walls are adequately reinforced, development of full grout strength results in increased joint capacity. The amount of wall reinforcement required to prevent splitting increases with grout compressive strength.
3. Filling slab cores with grout directly affects joint strength. For low-strength grouts, joint strength increases substantially with filled cores. With medium strength grouts, behavior at ultimate load changes from grout crushing to wall splitting when slab cores are filled. With both low and high strength grouts, wall reinforcement limits splitting. Thus, the benefits from filling the cores are utilized only when the grout strength is less than about 80% of wall concrete strength.
4. The quality of dry pack below the upper wall panel has a significant effect on the joint strength. Inadequate dry pack with voids leads to a substantial loss of joint capacity.
5. Floor moment and rotation do not have a significant effect on the strength of a wall-to-floor connection.

(Eq. B-7) agree very closely with the measured joint strength.

6.2 Exterior Joints

1. When grout strength is equal to or less than wall compressive strength, joint capacity increases with grout compressive strength.
2. Filled slab cores in exterior joints minimize the effects of built-in or accidental eccentricity. Joint strength, however, is not significantly improved.
3. When grout strength is less than or equal to wall compressive strength, wall splitting does not occur.
4. When the grout strength is greater than the wall strength, it is anticipated that wall splitting will occur unless the wall is adequately reinforced.
5. The proposed expression (Eq. B-8) gives conservative wall load capacities for exterior horizontal joints when compared with the measured strengths.

Detailed recommendations for specific analysis techniques and design criteria are given in Report 5⁽²⁾.

- A_g = cross-sectional area of grout column
 C = confinement factor
 E_1 = modulus of elasticity of upper wall panel
 E_2 = modulus of elasticity of dry pack
 E_3 = modulus of elasticity of grout in the joint
 E_4 = modulus of elasticity of lower wall panel
 f'_c = compressive strength of concrete
 f_g = compressive strength of grout in the joint
 f_u = maximum useable strength of grout for calculating joint strength
 $F.M.$ = fineness modulus
 K = stiffness factor
 L = horizontal length of grout column
 δl_1 = shortening measured over a height l_1 at the lower end of upper wall panel (See Fig. 17)
 δl_2 = shortening measured in dry pack, total height = l_2 (See Fig. 17)
 δl_3 = shortening measured in grout column, total height = l_3 (See Fig. 17)
 δl_4 = shortening measured over a height l_4 at the upper end of lower wall panel (See Fig. 17)
 $\delta l'_3$ = shortening measured in grout column over a height l'_3 (See Fig. 17)
 δl = $\delta l_1 + \delta l_2 + \delta l_3 + \delta l_4$ = total joint shortening measured over height $l = l_1 + l_2 + l_3 + l_4$ (See Fig. 17)
 LP = large panel
 P_g = vertical load transferred through grout column
 P_u = joint strength
 t = thickness of grout column
 σ = vertical stress in grout column

dental eccentricity:	An eccentricity which exists as a result of errors in either the manufacture or erection process.
assembly:	An aggregate of panels.
loading area:	Area of the wall panel through which the vertical compressive force is applied to the joint; 24 x 8 in. (610 x 203 mm) in the standard case.
out-of-plane eccentricity:	An eccentricity which exists as a result of the exterior joint configuration.
connections:	A position or region where two or more panels, including components, panels or assemblies are joined together or united.
connection stiffness: (vertical loads)	The sum of stiffnesses of grout and panels acting as "columns" composing a connection.
confinement factor:	A factor used to allow for increased compressive strength of grout, reflecting the confined nature of material in the joint.
continuity:	The capacity for load transfer between two or more elements where load is axial, bending moment, or any combination thereof.
failure pattern:	Mode of behavior at ultimate load.
distortion:	A change in dimension or shape.

Dry-packed mortar:	A mortar mixture sufficiently dry solidated by heavy ramming.
Ductility:	The measure of a structural c (element or joint) ability to inelastic deformations, i.e. the the maximum deformation to t deformation.
Exterior joints:	Horizontal joints connecting exter panels and floors.
Filled slab cores:	Hollow cores of precast concret filled with fluid grout (extendi 3-1/2 in. (89 mm) into the cores).
Floor moment and rotation:	Moment applied to simulate actual conditions (less than calculated moment).
Floor panel:	Horizontal precast concrete element cally consisting of hollow core concrete planks.
Floor plank:	A horizontal precast concret element cally extruded and reinforced with hi strength steel. Also known as holl or hollow-core slab.
Grout:	Mixture of cementitious material and gate to which sufficient water is a produce pouring consistency without gation of the constituents.

Grout stiffness ratio:	Ratio of grout column to the connection stiffness; also defined as a factor.
Grout strength:	Average compressive strength of grout used on six 6x12-in. (152x305 mm) test cylinders. Ranges of strength are: Low: 2500 to 4000 psi (17.2 to 27.6 MPa) Medium: 4000 to 5500 psi (27.6 to 37.9 MPa) High: 5500 to 7000 psi (37.9 to 48.3 MPa)
Horizontal joint:	The zone common to the wall and floor in a horizontal direction.
Integrity of connection:	The ability of a connection to transfer loads from one portion or element to another while retaining its structural strength.
Interior joints:	Horizontal joints connecting interior wall panels and floors.
Joint strength:	The maximum load sustained by a joint.
Large panel (LP) structures:	A structural system composed of large load-carrying elements of large panels with precast floors and walls or panels or planks.
Optimum wall reinforcement:	Minimum transverse reinforcement at the ends of wall panels to keep them from splitting before grout is placed at the joint.
Service load:	Unfactored normal loading conditions.

Strength of grout:	See grout strength.
Transverse wall reinforcement:	Optimum amount of reinforcement at the end of wall panels to limit
Ultimate joint load:	See joint strength.
Ultimate load: (general)	The maximum load which may be applied to a connection, member or a structure before failure; also, the load at which a unit or structure fails.
Wall panel:	A vertical precast concrete element, load-bearing or non-load-bearing, one-story in height, with length ranging from 10' to 45'.
Wall reinforcement:	See transverse wall reinforcement.

Assembly of Specimens

st specimen consisted of precast top and bottom wall panels, and precast concrete hollow-core slabs assembled as shown in Figs. 3 and 4. To assemble a specimen, the lower wall block was plastered to the floor. The hollow-core planks were lowered into position on top of it. The floor slabs were supported on 2-in. (51 mm) wide elastic bearing pads at the ends of the joint. The other ends of floor slabs were temporarily supported by screw jacks placed on concrete blocks as shown in Figs. 7 and 8. After testing, the screw jacks were replaced with load cells.

For a complete joint test, the grout in the joint extended about 3-in. (76 mm) into the slab cores to provide continuity. This was accomplished by placing crumpled newspapers as "dams" to stop the flow of grout at the desired point. In tests where the slab cores were deliberately blocked, the cores were completely blocked at the face using duct tape. The joint was then filled with grout.

The wall panel above the joint rested on dry-packed mortar about 1/2 in. (12 mm) thick. The mortar was packed from both sides of the wall to completely fill the joint.

Materials and Fabrication

C.2.1 Floor Elements

Hollow-core slabs used in all series had a design compressive strength of 5000 psi (34.5 MPa). Cross-sectional dimensions are shown in Fig. 23.

C.2.2 Wall Panels

Precast concrete wall panels were used. Top and bottom wall blocks were identical. A cross section is shown in Fig. 24.

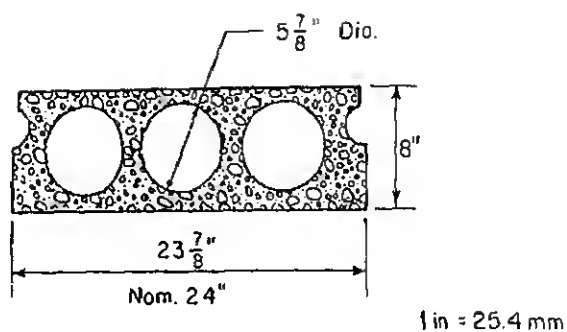


Fig. 23 Slab Cross Section

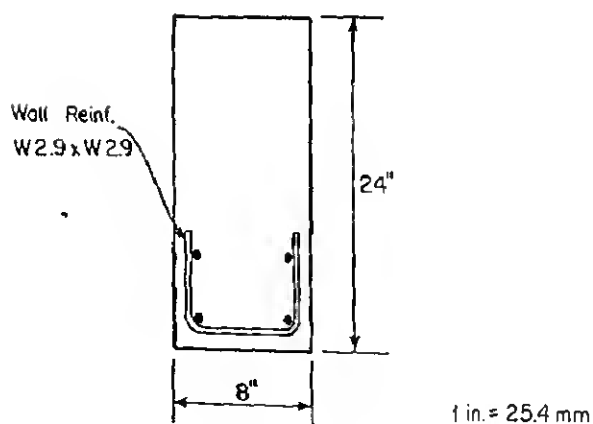


Fig. 24 Wall Cross Section

g Type I Portland Cement, Elgin Sand and Gravel with a maximum aggregate size of 3/4 in. (19 mm). The specimens and test cylinders were cured in the forms under plastic sheets for at least 3 days after casting. Compressive strength of concrete was determined from an average of nine 6x12-in. (152x305 mm) cylinders prior to testing. The results are given in Tables 2 and 3.

For some tests, both wall panels were reinforced at the ends with 6x6-
in. W2.9 reinforcement to limit splitting. The total amount of reinforcement provided in each wall was 0.116 in.² (75 mm²).

3 Grout and Mortar

Grout strength was one of the major variables. Tests were made with grout strengths of approximately 3000, 5000, and 7000 psi. (20.7, 34.5, and 48.3 MPa). Actual compressive strengths are listed in Tables 2 and 3.

Grout tests were made to determine the properties of fine aggregate and fluid grout prior to starting the test program on full-scale joint specimens. These tests are described in Appendix D.

A 1-in. (25.4 mm) thick dry-packed mortar was placed under the wall panel. The mixture contained equal parts by weight of Type I Portland Cement and Elgin Sand, and just enough moisture to make it workable. Steel metallic packers were used to ensure proper packing of the mortar layer.

The edges of grout and dry-packed mortar were covered with plastic sheets for at least 3 days curing after they were placed. Compressive strength of dry pack was usually higher than that of wall panels tested in the joint. A strength of about 9000 psi (62.1 MPa), was determined from the average of six 2x2-in. (50x50 mm) cubes tested at an age of approximately 5 days.

wall shortening and wall splitting. The layout of instrumentation for the interior joint test is illustrated in Fig. 25. Test setup for exterior joints was similar. Due to the built-in eccentricity of the exterior joint, the slab was also supported horizontally and the horizontal reaction was measured.

C.3.1 Forces

In the case of Specimen JM-1 with long slabs, two sets of load cells were used to measure the slab end reactions and the applied floor moment as shown in Fig. 5. The slab load was applied with hydraulic rams. Force was measured by a pair of load cells placed between the top slab and the cross heads on both sides of the connection.

All other tests were conducted with short slabs. The support reactions were measured by two 25-kip (111 kN) load cells placed on concrete blocks under the slabs.

C.3.2 Joint and Wall Shortening

Three 1-in. (25 mm) Linear Variable Differential Transformers (LVDT)⁽⁴⁾ were used to measure shortening of the joint, upper panel and the lower wall panel over a length of about 10 in. (0.25 m). Also, in some tests, an extra LVDT and a strain gage were used on the other side of the joint to measure shortening of the grout column also.

C.3.3 Wall Splitting

Two 0.001-in. (0.025 mm) dial gages were used to measure upper and lower wall splitting. The gages were mounted to detect changes in wall thickness. Tensile strains were also sensed underneath the upper wall panel by two 67-mm gage-length electrical strain gages⁽³⁾ mounted as shown in Fig. 25.

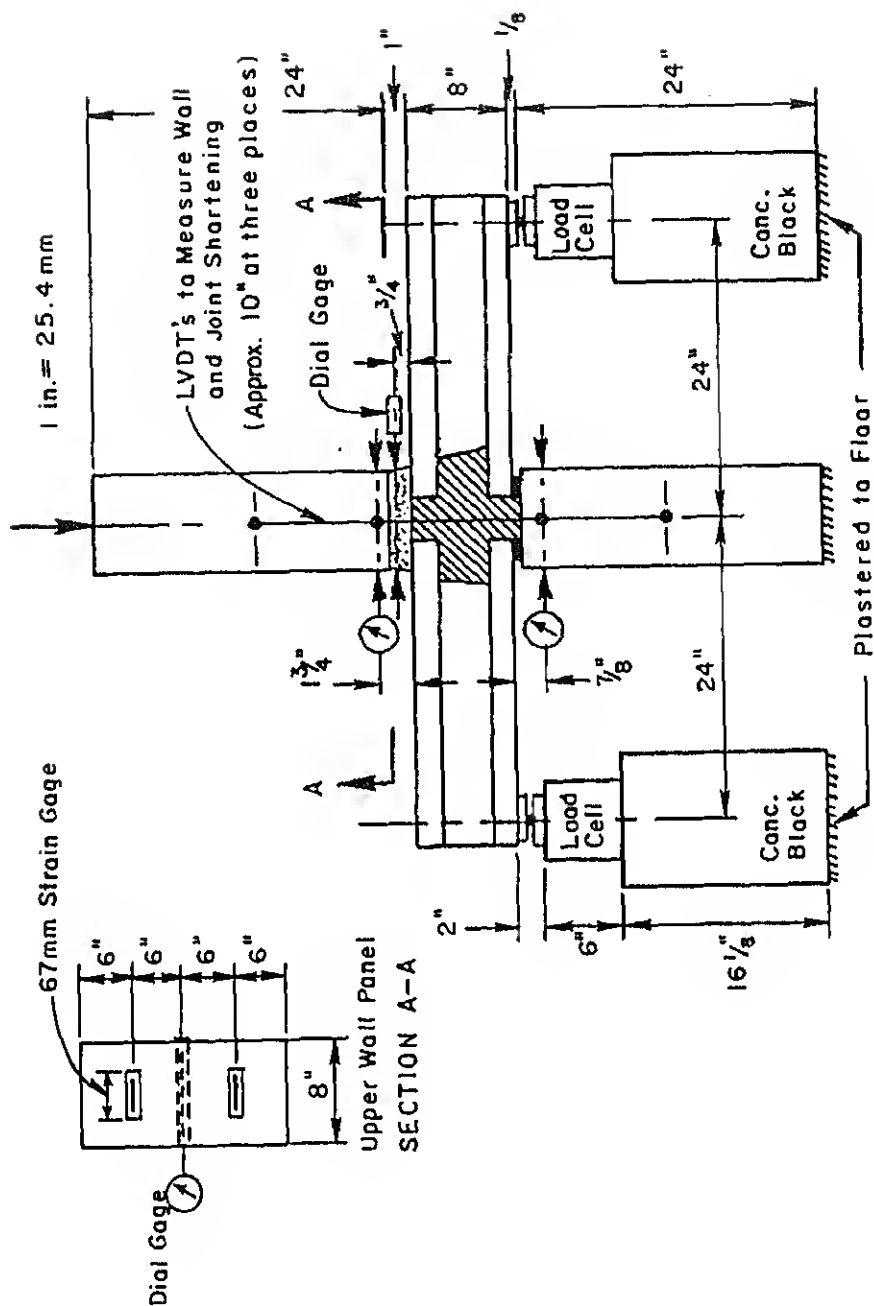


Fig. 25 Layout of Instrumentation for Interior Joint Test

All load cells, LVDT's and strain gages were connected to the Dig Data Acquisition System (DDAS). A mini computer was interfaced DDAS system to obtain simultaneously a magnetic tape record and print of raw data. The dial gages were recorded manually.

C.4 Test Procedure

Test setup and loading arrangement are shown in Figs. 7 and 8 for interior and exterior joints, respectively. A 1,000,000 lb. (4448 kN) test machine was used to apply the vertical compressive force. Load was applied through a 1-in. (25.4 mm) thick steel plate plastered to the top of upper wall panel. The specimen was centered below the loading head.

Specimens were loaded incrementally to destruction. The loading head of machine was locked by inserting wedges after two or three load stages.

Each specimen was loaded in about 25 increments. The size of increments reduced as the ultimate strength was approached.

After each load increment, measurements of all data were recorded. Cracks were identified and marked on the specimen in the order of their formation. Any other characteristics that occurred in the specimen after the initiation of the cracks were recorded also. The maximum load sustained was considered as the strength of the joint.

n objective of the tests was to determine the properties of
fill both longitudinal and transverse joints in LP structures.
e strengths were measured on 2-in. (51 mm) cubes, 2x4-in. (51x102
rs and 6x12-in. (152x305 mm) cylinders at 7 and 28 days. Te
ng tests were made on 2x4-in. (51x102 mm) cylinders at the same a

n variables included were:

Aggregate to cement ratio.

Water to cement ratio.

t program consisted of two series. Series A used an aggregate
ratio, by volume, of 3.0. Series B used a ratio of 2.25. For
the water to cement ratio, by weight, was varied from 0.37
Amounts of materials used for each batch of grout are shown in
nce there was always some free moisture present in aggregates.
mate adjustment was made each time to the amount of water added

TABLE 10 - GROUT CONSTITUENTS AND MIX WEIGHTS

Materials	Bulk Unit Weight lb./cu. ft.	Mix Weights, lb.	
		Series A	Series B
Type I Cement	94	40	40
Elgin Sand F.M. = 3.10	101	130	96
Water	62.4	Varied	Varied

Metric Equivalents: 1 lb. = 4.448N

1 cu. ft. = 0.02832 cu.m.

tively, Construction Engineer, Construction Methods Section
g Senior Structural Engineer, Structural Development Sec
d Cement Association, Old Orchard Road, Skokie, Illinois.

for about 48 hours after fabrication. The specimens were then demolded and stored in the moist room until about two hours before testing. The cylindrical specimens for compression tests were capped with high strength capping compound and the caps were allowed to cure at least one hour before compression testing. The strengths of grout were determined from the average of at least four specimens.

D.2 Test Results

Average grout strength versus water-cement ratio are shown in Figures 28 through 29. Average values for each series are given in Table 11.

The tests indicated that when the grout was either too stiff or too fluid, the results were inconsistent. When the water-cement ratio was too low, compaction was a problem, and inconsistency resulted from a nonuniform distribution. With high water-cement ratio, the mix was very fluid. Compaction was not required. However, heavier particles tended to settle down leaving a thin layer of water on top. Also, the mix had to be constantly agitated while the specimens were being cast.

Based on these tests, it appears that the most appropriate water-cement ratio to achieve good workability and consistency would be in the range of 0.5 to 0.75 with an aggregate-cement ratio of 3.0, and between 0.625 and 0.75 for an aggregate-cement ratio of 2.25.

Tests were also made to determine the fineness modulus, moisture content, unit weight, and specific gravity of sand that was used as fine aggregate in the grout mix. The results of tests on fine aggregate are tabulated in Table 12. The gradation curve shown in Fig. 30, was plotted from the results of the standard sieve analysis. The material conformed to the requirements.(7)

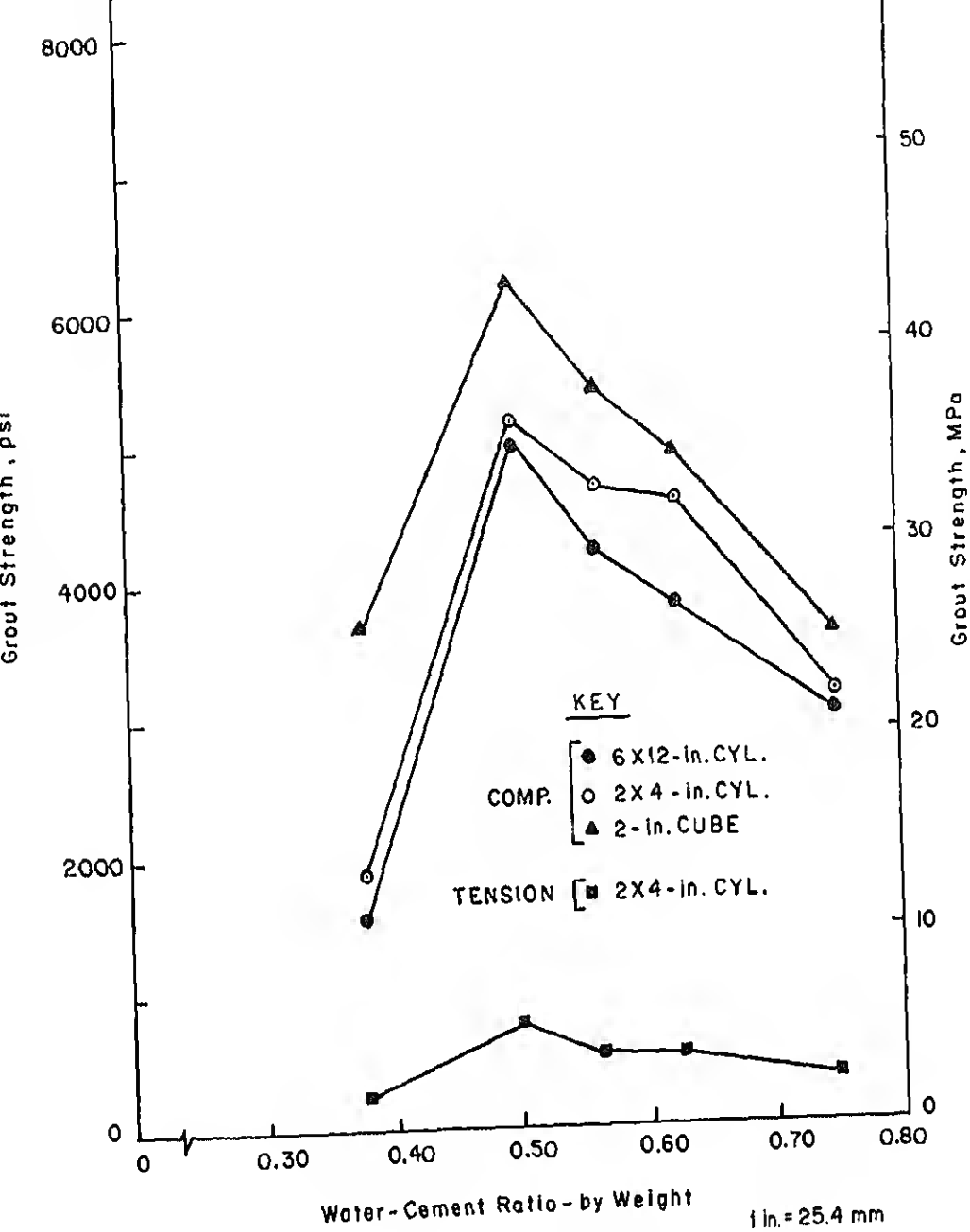


Fig. 26 Strength versus Water-Cement Ratio at 7 Days for Series A

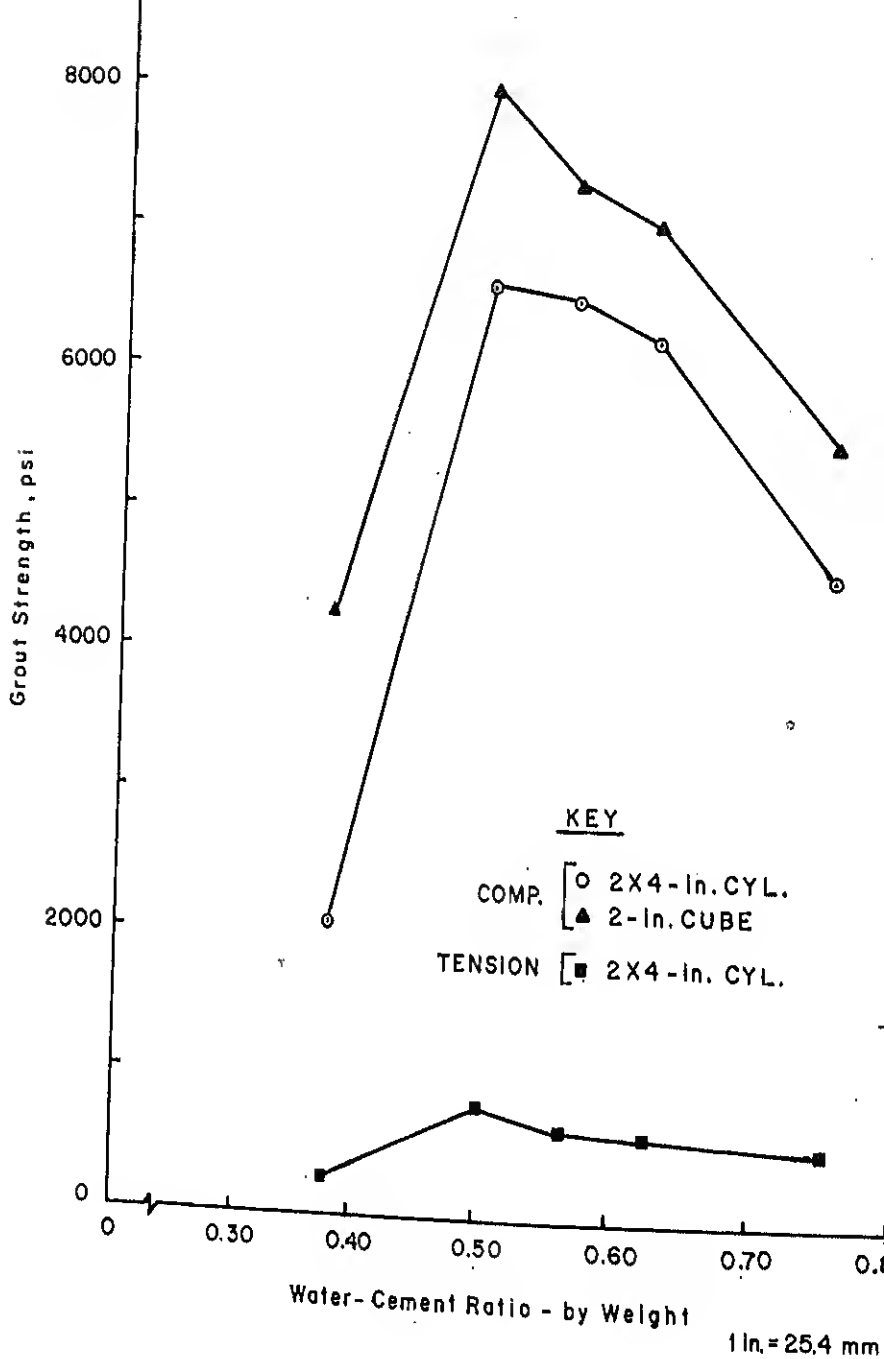


Fig. 27 Strength versus Water-Cement Ratio at 28 Days for S

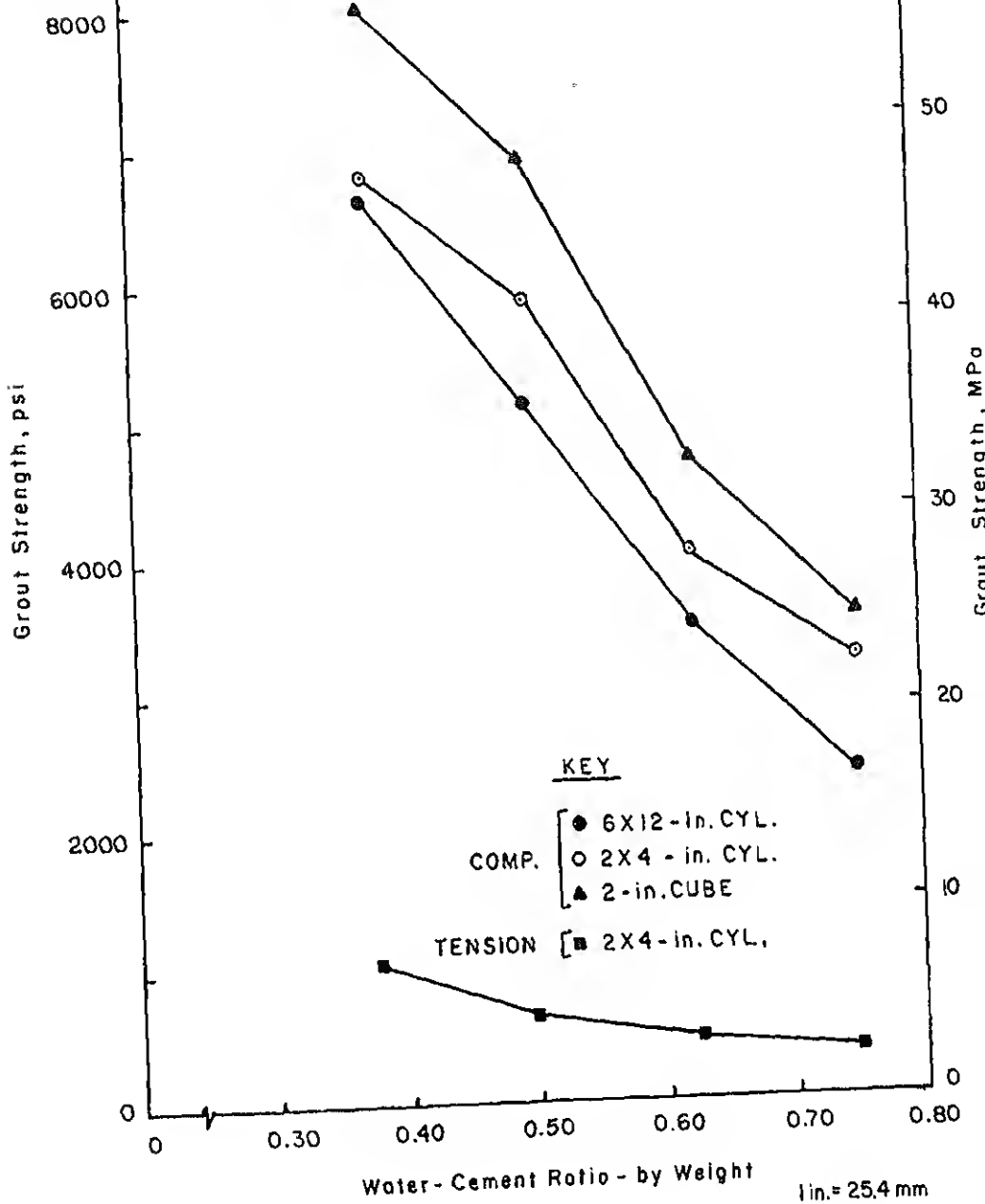


Fig. 28 Strength versus Water-Cement Ratio at 7 Days for Series B

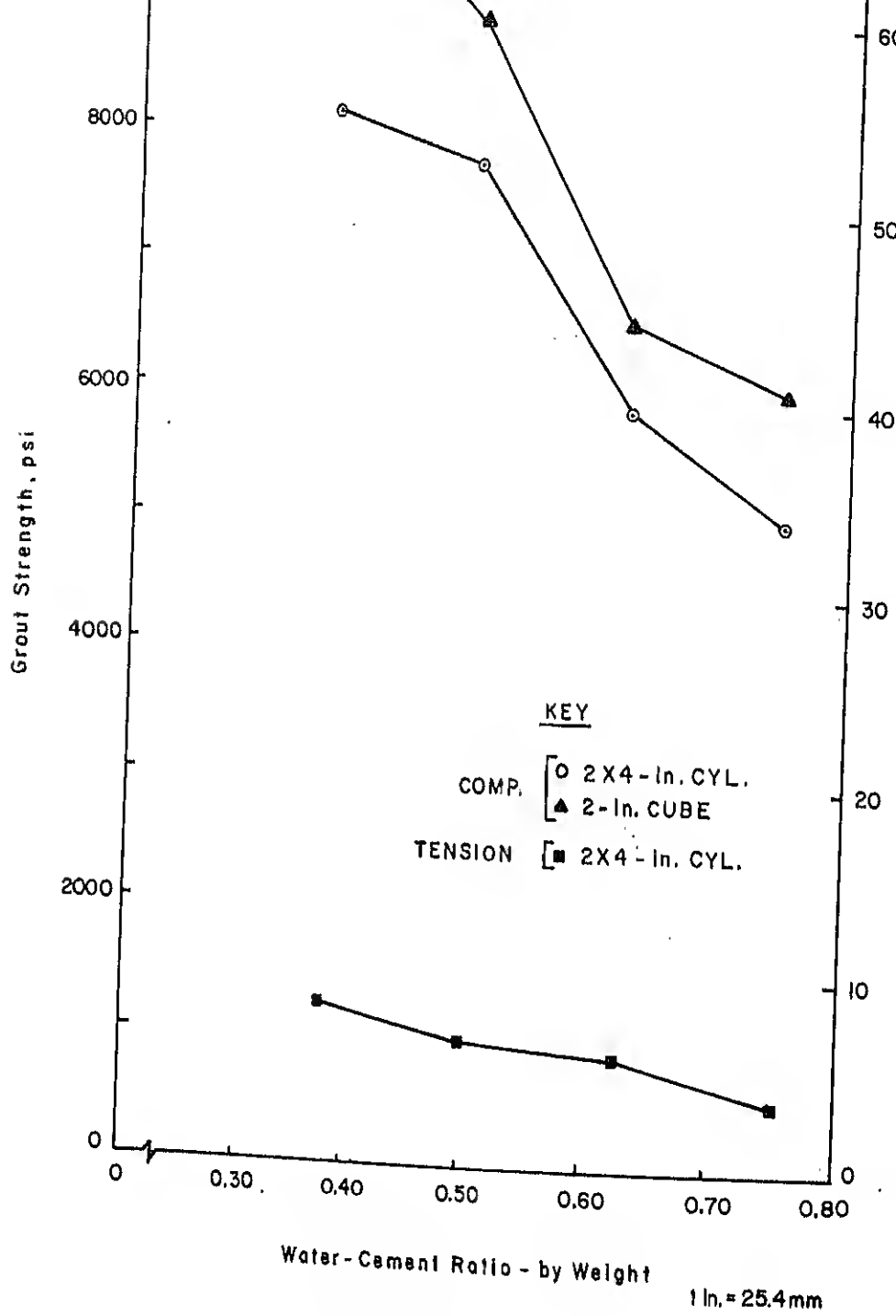


Fig. 29 Strength versus Water-Cement Ratio at 28 Days for Series I

Aggregate-Cement Ratio (by volume)	Water-Cement Ratio (by weight)	Average Compressive Strength* (psi)						Avg. Tensile Strength* (psi)
		2-in. Cubes		2x4-in. Cyl.		6x12-in. Cyl.		
		7 Days	28 Days	7 Days	28 Days	7 Days	28 Days	
3.0	0.375	3700	4240	1880	2070	1550	250	270
	0.500	6220	7890	5190	6510	5040	770	800
	0.562	5490	7220	4720	6490	4250	530	650
	0.625	4990	6960	4610	6170	3880	510	620
	0.750	3610	5460	3180	4510	3060	360	540
2.25	0.375	8050	10000	6830	8050	6640	1040	1240
	0.500	6970	8750	5920	7660	5130	650	980
	0.625	4710	6410	4030	5790	3550	480	860
	0.750	3570	5900	3240	4940	2400	350	510

* Average strength of at least four specimens.

Fineness Modulus		3.10
Moisture Content		3.14 %
Specific Gravity		2.73
Unit Weight (pcf)	Natural	101
	Dry	115

Metric Equivalent: 1 pcf = 16.02 kg/cu.m

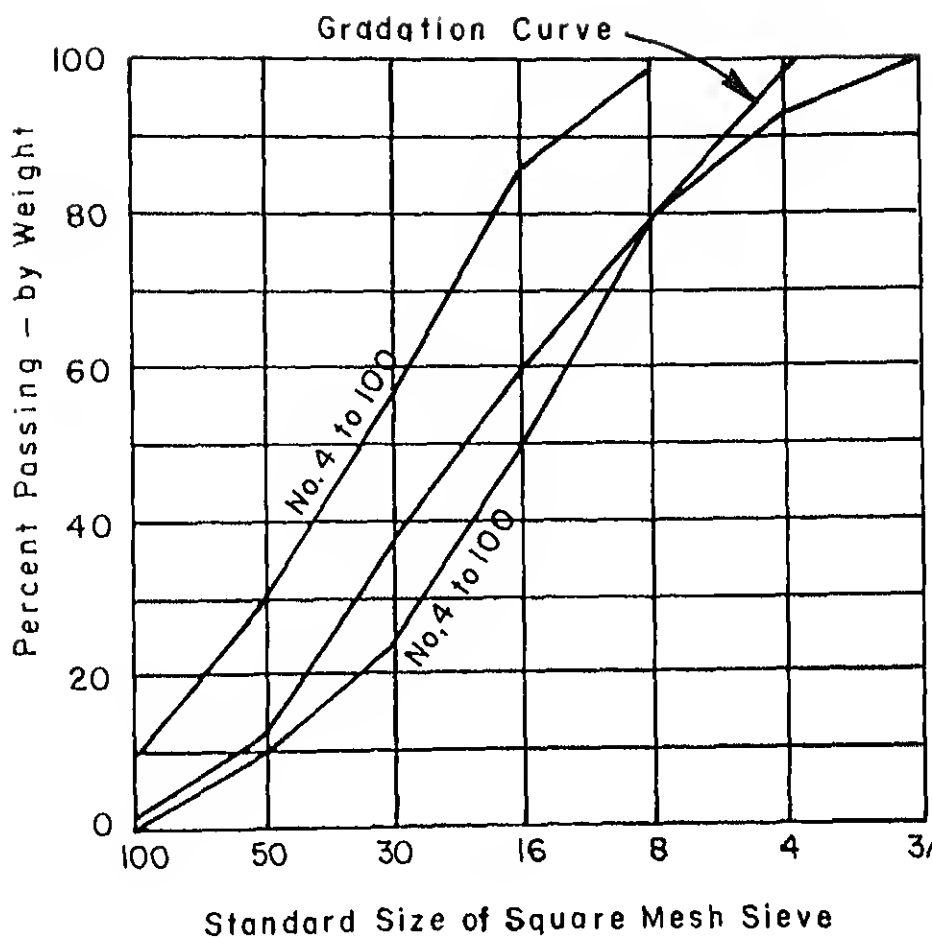


Fig. 30 Gradation Curve for fine Aggregate

ACKNOWLEDGEMENTS

This investigation was carried out at the Structural Laboratory of Portland Cement Association under the direction of Dr. H. G. Russell, Structural Development Section and Dr. W. G. Corley, Director, Engineering Development Department. Particular credit is due B. Wm. Fullhart, Jr. and Wm. Hummerich, Jr. for their assistance in the manufacture and testing of the test specimens and Mr. M. Fintel, Advanced Engineering Services Department, Portland Cement Association, for overall project supervision. Mr. D. M. Schultz, Senior Structural Engineer, Structural Development Section contributed significant direction in design of the test specimens, conduct of the tests and interpretation of the data.

tel, M., Schultz, D.M., and Iqbal, M., "Report 2: Philosophical and Structural Response to Normal and Abnormal Loading Conditions," Design and Construction of Large Panel Concrete Structures, Office of Policy Development and Research, Department of Housing and Urban Development, Washington, D.C., August 1976. Also PCA Publication EB92.

Schultz, D.M., Johal, L.S., Derecho, A.T. and Iqbal, M., "Report 3: Special Topics," Design and Construction of Large Panel Concrete Structures, Office of Policy Development and Research, Department of Housing and Urban Development, Washington, D.C., January 1979. Also PCA Publication EB95.

Weststad, E., Hanson, N.W., Kriz, L.B., and Kurvits, O.A., "Facility Test Methods of PCA Structural Laboratory," Journal of the Portland Cement Association, Research and Development Laboratories, Vol. 1, No. 3, 1957; Vol. 1, No. 3, 1959, pp. 35-41; PCA Development Bulletin D33.

Hanson, N.W., Hsu, T.T.C., Kurvits, O.A., and Mattock, A.H., "Facility Test Method of PCA Structural Laboratory - Improvements 1960-1965," Journal of the Portland Cement Association, Research and Development Laboratories, Vol. 3, No. 2, May 1961, pp. 27-31; Vol 7, No. 1, January 1965, pp. 2-9; and Vol. 7, No. 2, May 1965, pp. 24-38; PCA Development Bulletin D91.

Committee on Precast Bearing Wall Buildings, "Consideration for Design of Precast Bearing Wall Buildings to Withstand Abnormal Loading," Journal of the Prestressed Concrete Institute, Vol. 21, No. 2, March 1976.

Committee on Construction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry," (C780-74) American Society for Testing and Materials, Philadelphia, part 16, 1977, pp. 436-451.

Standard Specification for Concrete Aggregates," (C33-77) American Society for Testing and Materials, Philadelphia, part 14, 1977, pp. 14-17.

Canadian customary value by the conversion factor. For example, to convert 11.4 ft. to meters: 11.4 ft. \times 0.3048 = 3.47472 which rounds to 3.47 meters for an accuracy of two significant digits. Do not round before performing the multiplication, as accuracy would be reduced. A complete guide to the use of the International System of Units).

To convert from	to	multiply
<u>Length</u>		
inch (in.)	centimeter (cm.)	
inch (in.)	meter (m.)	
foot (ft.)	meter (m.)	
yard (yd.)	meter (m.)	
<u>Area</u>		
square foot (sq.ft.)	square meter (sq.m.)	
square inch (sq.in.)	square centimeter (sq.cm.)	
square inch (sq.in.)	square meter (sq.m.)	
square yard (sq.yd.)	square meter (sq.m.)	
<u>Volume</u>		
cubic inch (cu.in.)	cubic centimeter (cu.cm.)	
cubic inch (cu.in.)	cubic meter (cu.m.)	
cubic foot (cu.ft.)	cubic meter (cu.m.)	
cubic yard (cu.yd.)	cubic meter (cu.m.)	
gallon (gal.) Can. liquid**	liter	
gallon (gal.) Can. liquid**	cubic meter (cu.m.)	
gallon (gal.) U.S. liquid**	liter	
gallon (gal.) U.S. liquid**	cubic meter (cu.m.)	
<u>Force</u>		
kip	kilogram (kgf)	4
kip	newton (N)	4,4
pound (lb.)	kilogram (kgf)	
pound (lb.)	newton (N)	
<u>Pressure or Stress</u>		
kip per square inch (ksi)	kilogram per square centimeter (kg/sq.cm.)	
pound per square foot (psf)	kilogram per square meter (kg/sq.m.)	
pound (force) per square foot (psf)	pascal (Pa.)†	
pound per square inch (psi)	kilogram per square centimeter (kg/sq.cm.)	
pound (force) per square inch (psi)	pascal (Pa.)†	6,8
<u>Mass (Weight)</u>		
pound (lb.) avdp.	kilogram (kg)	
ton, 2,000 lb.	kilogram (kg)	90
grain	kilogram (kg)	
<u>Mass (weight) per Length</u>		
kip per linear foot (klf)	kilogram per meter (kg/m.)	
pound per linear foot (plf)	kilogram per meter (kg/m.)	
<u>Mass per Volume (Density)</u>		
pound per cubic foot (pcf)	kilogram per cubic meter (kg/cu.m.)	
pound per cubic yard (pcy)	kilogram per cubic meter (kg/cu.m.)	
<u>Temperature</u>		
degree Fahrenheit (deg. F.)	degree Celsius (C)	$t_C = (t_F - 32) \times \frac{5}{9}$
degree Fahrenheit (deg. F.)	degree kelvin (K)	$t_K = (t_F - 32) \times \frac{5}{9} + 273.15$
<u>Energy</u>		
British thermal unit (Btu)	joule (J)	1,055
kilowatt-hour (kwh)	joule (J)	3,600,000
<u>Power</u>		
horsepower (hp) 550 ft.-lb./sec.	watt (W)	746
<u>Velocity</u>		
mile per hour (mph)	kilometer per hour	
mile per hour (mph)	meter per second (m./s.)	

*E indicates that the factor given is exact.

**One U.S. gallon equals 0.8327 Canadian gallon.

†A pascal equals 1.000 newton per square meter.

